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THE MOVEMENT OF WATER IN IRRIGATED SOILS[1]

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INTRODUCTION

Irrigation is a relatively new feature of agriculture in the United States. As yet there has not been time to accumulate a fund of experience in irrigation to correspond to our knowledge of farming under conditions of ample rainfall. We are now practicing irrigation under a great variety of conditions as to climate, soil, and character of water supply, and are gaining experience rapidly. Large investments have been made in irrigation works and in the improvements and equipment on irrigated land. These investments include not only money but even in larger measure the labor of the farmer and home maker, which have been applied in the belief that irrigation farming is no less permanent than farming under conditions of adequate rainfall. The structures installed for the storage and diversion of irrigation water have been built to last for generations. It is clearly the expectation that the lands to be served by this water will continue to be productive as long as the works shall stand. Yet our own experience, which covers but little more than half a century, shows that there is a real danger that some of our irrigated lands may become unproductive within a few years. The causes of this uncertainty as to the future are found in what is known as the alkali problem.

The present paper deals with certain aspects of the alkali problem which as a whole relates to the soluble salts in the soil solution. These salts, which are derived from the processes of rock decomposition and soil formation everywhere, do not accumulate in the soil except in arid regions where the evaporation exceeds the rainfall. In regions of abundant rainfall the soluble products of rock decomposition are continually leached away from the soil and carried to the sea.

In attempting to present an account of the alkali problem in relation to irrigation farming it seems desirable to consider first the physical relations existing between the water and the soil. An understanding of these relations is essential to a comprehension of the alkali problem. In an irrigated field the soil acts as a reservoir to hold water for the use of plants. As a reservoir it has definite limits of capacity, both as to the quantity of water it may hold within the zone occupied by plant roots and as to the time required to fill it with water. These limits and the factors which determine them need to be understood as clearly as our knowledge permits, both by the farmer who operates the land and by the engineer who designs and constructs the irrigation works.

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SOIL WATER

In an irrigated field the soil water that is of chief concern to the farmer is the water that exists in the surface layer of the soil from 4 to 10 feet deep, depending on the character of the crop for which the field is used. This surface layer of soil serves as a reservoir in which to store water from time to time by irrigation, so that it may be continuously available to the crop plants during the growing period.

The water that is put into this surface layer of soil may not all be used by plants. On the one hand, if the soil is saturated with water, the roots of most crop plants do not function properly. If the roots have been established before the soil becomes saturated they may die below the level of saturation. If the soil is already saturated the roots do not penetrate the saturated zone. Consequently, a soil may contain too much water to support the growth of crop plants. This condition is not uncommon in irrigated lands, and such lands are referred to as "water-logged."

On the other hand, some of the water in the soil is not available to plants because it is held so firmly by the soil that the plants can not use it. When the moisture content of the soil is so low that plants can not obtain from it enough water to maintain their growth there still remains an appreciable quantity of water in the soil. It is customary to refer to the moisture condition of the soil at which plants can not obtain water for growth as the wilting point. It is only the water that is in excess of the moisture content at the wilting point that is available to crops or that constitutes the available reservoir capacity of the soil.

The upper limit of the reservoir capacity of the soil is a point well below the saturation point. This upper limit is commonly referred to as the maximum field carrying capacity. The maximum field carrying capacity of a soil is not susceptible of accurate determination because it is conditioned by forces that are constantly changing.

THE WATER-HOLDING CAPACITY OF SOIL

It is generally assumed that the specific gravity of soil material is 2.65, so that if we could conceive of a cubic foot of soil so compressed as not to contain any voids it would weigh 165 pounds. As a matter of fact, as it occurs in the field, soil is found generally to range in weight from 75 to 105 pounds per cubic foot, with a few exceptional cases in which it weighs less or more than the figures given. These figures refer to the dry weight of the volume of soil.

If we assume that the soil material has a specific gravity of 2.65, then it is possible to compute the pore space in a volume of soil, e. g., a cubic foot, when this volume has various weights. Thus if 1 cubic foot of soil without pore space weighs 165 pounds and a cubic foot of soil with pore space weighs 85 pounds, then:

$$\text{Pore space} = \frac{165-85}{165} = 48.5 \text{ per cent},$$

or a cubic foot of dry soil which weighs 85 pounds may be said to have 51.5 per cent of its volume occupied by soil material and 48.5 per cent of its space existing as voids. If this void space were filled with water, that is, if the soil were saturated, but without changing the volume, then the soil would be said to hold 35.6 per cent of water. That is to say, if a cubic foot of water weighs 62.4 pounds, the water which occupies 48.5

per cent of that cubic foot weighs 30.26 pounds. If the dry soil in this cubic foot weighs 85 pounds, then 100 pounds of soil under the same condition of saturation would hold 35.6 pounds of water.

In like manner it is possible to compute the pore space and the water-holding capacity in percentage of water to the dry weight of the soil for any given case where the volume mass of the dry soil is known. Table I shows these relationships for several different weights of soil, and these are presented graphically in figure 1.

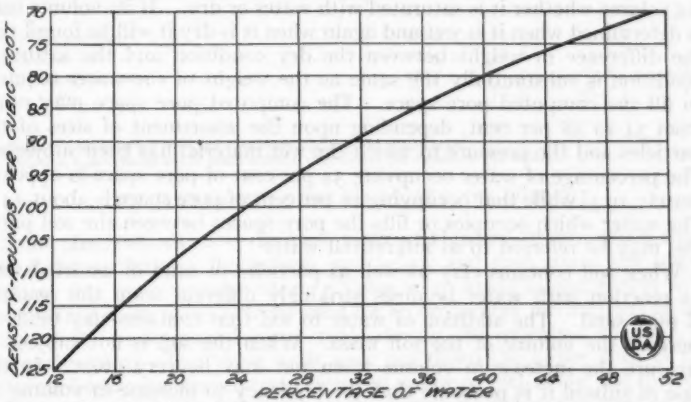

FIG. 1.—Diagram showing water-holding capacity of soil at densities ranging from 70 to 125 pounds per cubic foot, based on specific gravity of 2.65.

TABLE I.—*Pore space in dry soil of different weights per cubic foot based on the specific gravity of 2.65 for the soil material and the moisture content if this pore space were filled with water*

Weight of dry soil per cubic foot.	Pore space.	Water in saturated soil.	Water per foot of soil.[a]
Pounds.	*Per cent.*	*Per cent.*	*Inches.*
70	57.6	51.4	6.9
75	54.6	45.4	6.5
80	51.5	40.2	6.2
85	48.5	35.6	5.8
90	45.5	31.5	5.5
95	42.4	27.9	5.1
100	39.4	24.6	4.7
105	36.4	21.6	4.4
110	33.3	18.9	4.0
115	30.3	16.4	3.6
120	27.3	14.2	3.3
125	24.2	12.1	2.9

[a] By this is meant the equivalent, in inches in depth, of water contained in each foot in depth of soil.

It is not always an easy matter to determine the volume mass or the weight per cubic foot of the dry soil as it occurs in field conditions. The soil in the field is never entirely dry, and it may lose volume as well as weight when dried after being taken from its position in the field. It is this property of the soil by which it tends to increase its volume when

wet and to shrink on drying that constitutes one of the chief difficulties in the way of a clear understanding of its water-holding capacity. Soils differ greatly with respect to changes in volume that take place when they are alternately wetted and dried. Pure sand does not change its volume materially whether it is saturated with water or dry. Soil containing clay, on the other hand, swells extensively when wet and shrinks again when dried.

It is possible to demonstrate that a certain volume of pure sand retains its volume whether it is saturated with water or dry. If its volume mass is determined when it is wet and again when it is dry it will be found that the difference in weight between the dry condition and the saturated condition is substantially the same as the weight of the water required to fill the computed pore space. The computed pore space may range from 34 to 28 per cent, depending upon the assortment of sizes of the particles and the pressure to which the wet material has been subjected. The percentage of water occupying 34 per cent of pore space is approximately 19.5, while that occupying 28 per cent of pore space is about 14.6. The water which occupies or fills the pore spaces between the soil particles may be referred to as interstitial water.

When soil contains clay as well as particles of sand of assorted sizes its reaction with water becomes strikingly different from the reaction of pure sand. The addition of water to soil that contains clay tends to increase the volume of the soil mass. When the soil is not subject to pressure the increase in volume when wet may be very great. In the case of subsoil it is probable that the tendency to increase in volume on wetting is met by the pressures that develop within the soil mass. The quantity of water that may be absorbed by the soil some distance below the surface is very much less than the same soil will hold if it is at the surface.

These differences of water-holding capacity have been demonstrated by a series of tests made at the Newlands Experiment Farm by F. B. Headley.[3] Samples of subsoil were taken with a soil tube in places where free underground water was found within 2 to 3 feet of the surface. The soil samples were taken from below the level of the ground water. The moisture content was determined on the samples obtained with the soil tube, and the dried samples were then pulverized, sifted, and placed in metal cups of 20 cc. capacity having perforated bottoms. The soil in these cups was then saturated with water and weighed to determine its water-holding capacity in the absence of pressure. In texture the soil samples ranged from coarse sand to fine clay. For convenience in comparison they are arranged in Table II in groups with respect to texture. The results of these tests show that there are not only marked differences in the water-holding capacity of soils of different textures as they exist in the lower part of the root zone but that the water-holding capacity of the same soil is much greater when it is on the surface and freed from pressure than when it lies some distance below the surface and is subject to pressure.

[3] These experiments were made at the writer's request during August, 1923.

TABLE II.—*Water-holding capacity of soil of different types, as found at 2 to 4 feet below the surface in the field and as determined in shallow perforated cups in the laboratory* [a]

Samples and texture of soil.	Average water-holding capacity (percentage of dry soil)—		Increase.	Comparative increase. [b]
	In the field.	In the laboratory.		
				Per cent.
No. 5, coarse sand	18.0	25.4	7.4	41
No. 8, fine sand	21.5	36.6	15.1	70
No. 7, sandy loam	20.7	41.5	20.8	100
No. 4, clay	33.5	78.7	45.2	135

[a] Reported by Headley from the Newlands Experiment Farm, 1923.
[b] Stated as a percentage of the water-holding capacity of the sample in the field.

THE WATER-HOLDING CAPACITY OF SUBSOIL

Some observations have also been made at Huntley, Mont., which show the water content of the subsoil just below and just above the upper limit of free underground water.[3] These were made in connection with the putting down of wells to be used for recording the fluctuations of the level of the underground water table during the irrigation season. In the early spring when these wells were put down the upper limit of the saturated zone was encountered between 9 and 12 feet below the surface.

The water content of the soil in the zone just below the level of the ground water is given in Table III. This shows that the saturated subsoil contained approximately 25 per cent of water. By reference to Table I, which shows the percentage of water in saturated soils of various densities, it will be seen that this Huntley subsoil may be assumed to have an average density of 99 pounds of dry soil per cubic foot. Thus, each cubic foot of the saturated subsoil contains 99 pounds of soil and 25 pounds of water. This 25 pounds of water per cubic foot is equivalent in volume to 4.8 inches of water per square foot of area.

In connection with the moisture determinations described above, tests were made of the moisture content of the subsoil just above the level of the ground water. These latter determinations were made on samples representing 6-inch layers, none of which was more than 2 feet above the point of saturation, and most of them were within 1 foot above it. There were in all 80 moisture determinations on the soil just above the water line, and these gave a mean of 24.8 ± 0.25. This mean when compared with the mean of 25.4 ± 0.2 for the 30 samples reported in Table III shows that there is very little difference in the moisture content of the soil just above and just below the level of the underground water.

These results indicate that it takes very little change in the actual volume of the underground water to cause a marked change in level. It would take only a small contribution of percolating water from above to cause the ground-water level to rise; conversely, the removal of a small volume of water by drainage would lower the ground-water level. The volume relations involved in raising or lowering the ground-water level are probably different with different soil types. Very little informa-

[3] These observations were made at the writer's request by Dan Hansen, Superintendent of the Huntley Experiment Farm.

tion is available concerning these relations. In the case of the soils at Huntley, the figures reported would indicate that a change in water content of 0.6 per cent in the critical zone would change the water level 1 foot.

TABLE III.—*Moisture content of soil saturated with underground water, Huntley, Mont., May, 1923*

Well No.	Depth.	Texture of soil.[a]	Moisture.
			Per cent.
A2	12. 5	SCC	24. 0
	13. 0	SSC	25. 6
	14. 0	SSC	24. 8
A4	13. 5	SSC	25. 3
A6	11. 0	SSC	28. 1
A7	11. 0	SCC	27. 4
B1	11. 0	SSC	25. 1
	11. 5	SSC	24. 6
B2	10. 5	SSC	25. 7
	11. 0	SSC	26. 0
B3	11. 0	SSC	23. 4
B4	11. 0	SCC	25. 6
	11. 5	SCC	26. 5
B6	10. 5	SS	29. 6
B7	9. 5	SSC	25. 0
B8	9. 5	SSC	25. 0
	10. 0	SSC	24. 7
C4	10. 5	SS	22. 2
	11. 0	SS	22. 7
C6	10. 5	SSC	26. 4
	11. 0	SSC	24. 6
C7	10. 0	SSC	25. 4
C8	10. 5	SS	23. 5
	11. 0	SS	23. 0
C9	10. 5	SSC	24. 1
	11. 0	SS	23. 1
C10	11. 0	SS	26. 1
	11. 5	SS	25. 6
C11	10. 5	SSC	27. 6
	11. 0	SCC	30. 8
Mean			25. 4±0. 2

[a] The letters S and C refer to the proportions of sand and clay judged by observation.

An experiment in lowering the ground-water table by pumping, reported from the Salt River Valley, Ariz., (7)[4], affords a basis for estimating the quantity of water involved in a change of level of underground waters. In this experiment a well was put down 285 feet deep where the water table was 3 feet below the surface. Water was pumped for 630 hours during a period of 34 days, with a total discharge of 77.9 acre-feet. The maximum draw down at the well was 73 feet. The radius of measurable depression of the water table was 2,350 feet, while the radius of pronounced depression was 1,150 feet. It was computed that for the inner area of 95 acres the water table was lowered 4.4 feet and for the outer area of 300 acres it was lowered 0.6 of a foot. The removal of 77.9 acre-feet of water cleared 598 acre-feet of subsoil of its

[4] Reference is made by number (italic) to "Literature cited," p. 692–693.

free water, which is to say that the removal of 1 acre-foot of water changed 7.7 acre-feet of subsoil from a saturated to an unsaturated condition. In other words, the removal of 1.56 acre-inches of water lowered the water table 1 acre-foot. It is probably safe to assume that under the conditions of this experiment there was some inflow of water from the surrounding saturated subsoil that was not observed, so that the ratio 1.56 acre-inches per acre-foot is probably too high rather than too low.

F. H. King (*12, p. 132-134*) has reported on the water content of undisturbed field soils when saturated and when only the bottom inch of each 1-foot section was saturated. From his figures for soil from the third, fourth, and fifth foot sections, there was an average difference of 0.4 of an inch less water in the soil when the bottom only was saturated than when the whole of the section was saturated. In another experiment King set up columns of soil 7 feet long which were first saturated and then allowed to stand for 60 days with the bottom of the soil column in water and the top protected from evaporation. The columns were then cut into 6-inch sections and the water content of each section was determined.

In the results reported by King for this experiment, if the top and bottom 6-inch sections be eliminated, it is found that the water content decreases fairly consistently from the lower to the upper sections. Where the soil used was classed as sandy loam the decrease in water content of each 6-inch section from below upward was at the rate of 0.6 per cent. With the soil classed as clay loam the rate of decrease was slightly less than 0.5 per cent per section.

These figures when converted into inches of water for each 1-foot layer of soil give an average decrease of water of slightly more than 0.1 of an inch for the sandy loam and slightly less than 0.08 of an inch for the clay loam.

It would appear from such evidence as is available that when considering only the layer of subsoil immediately above the level of underground water, the addition of 0.1 of an inch of water would result in raising the ground-water level 1 foot. As a matter of fact, it would not be correct to conclude that the removal of a volume of water equal to 0.1 of an inch in depth would lower the underground water level as much as 1 foot or that the addition of that quantity would raise it 1 foot for the reason that any change in water level would affect the moisture conditions for some distance above the water line.

The extent of the change of moisture conditions of the subsoil consequent upon or necessary to produce a change of 1 foot in the ground-water level would be influenced materially by the texture and density of the soil material. It is probable that in some situations the addition or removal of half an inch of water might raise or lower the ground-water level 1 foot while in other situations it might require 1½ inches to cause the same change. Speaking generally, it may be assumed that the addition or removal of 1 inch of water may raise or lower the ground-water level 1 foot.

CONDITIONS OF SOIL WATER

It has been customary to say that water may be contained in the soil in three different conditions which are designated as follows:

(1) Hygroscopic water, or water that is held by the soil when in equilibrium with the air.

(2) Capillary water, or water that is held as liquid films around the soil particles in such a way as to exert no hydrostatic pressure; in other words, in equilibrium with the force of gravity, but not in equilibrium with the air.

(3) Hydrostatic water, or water that exists in the soil, but subject to movement in response to the force of gravity unless such movement is hindered by some barrier.

While this classification is useful in connection with the study of the physical properties of soils, it does not serve so well in dealing with the relations between the soil and the crop plant. The soil may be regarded as a reservoir which is replenished with water from time to time by rainfall or by irrigation, from which there may be losses by percolation or evaporation and from which the plant draws its daily supply. The effective reservoir capacity of the soil is limited on the one hand by

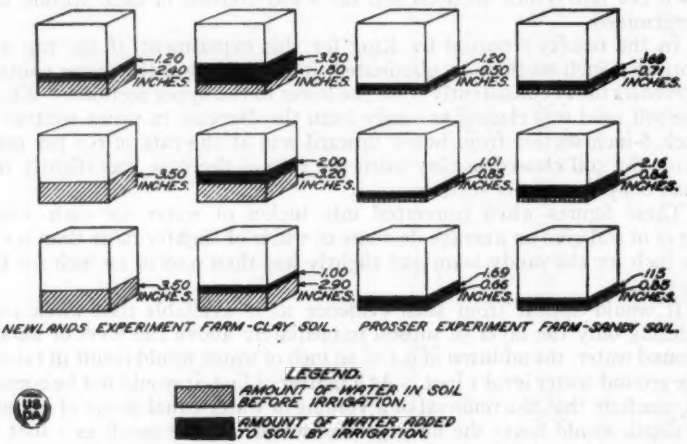

FIG. 2.—Quantity of water held before and after irrigation by two soils.

the fact that most crop plants do not thrive when the soil is saturated with water so that air is excluded and on the other hand by the fact that plants can not absorb all of the water held in the soil.

From the standpoint of its use by crop plants, the soil water may be classified as to condition as follows:

(1) Subavailable water, or that portion of the soil water which is held by the soil when plants can no longer obtain water for the normal processes of growth. The moisture content of the soil which represents the upper limit of the subavailable supply is often referred to as the wilting point of the soil.

(2) Available water, or that portion of the soil water that is in excess of the subavailable supply and has an upper limit somewhat below the saturation point.

(3) Superavailable water, or that portion of the soil water between the saturation limit and the limit above which plant roots do not function normally, presumably because of lack of air.

The soils which one finds in irrigated fields differ so greatly from place to place that it is impossible to indicate in any precise way how much water any soil may hold, even were it possible to establish definitely

the limits of the classes of soil water listed above. The class of water with which the irrigation farmer is chiefly concerned is the one designated available water.

The quantity of this available water that may be added to a soil by an irrigation may be determined by sampling the soil to the depth of the root zone when the crop shows evidence of needing irrigation and sampling again to the same depth as soon as possible after irrigation. The increase in moisture content of the soil shows how much available water has been added by irrigation.

The results of such an investigation with reference to two very different types of soil are shown in Table IV. The figures in the table give, in terms of the percentage of water to the dry weight of the soil, a measure of the increase in the water supply of the 3-foot layer of soil due to an irrigation. These percentage figures may be converted into their equivalents in terms of inches of water for each foot of soil and thus express the volume of water in a more concrete way than the percentage statement does. The volume relations of the soil and the water it contains are shown in figure 2, which is based on Table IV. In converting percentages of water to inches of water it was assumed that the clay soil had a density of 85 pounds per cubic foot and the sandy soil a density of 82 pounds per cubic foot.

TABLE IV.—*Quantity of water in the soil to the depth of 3 feet before and after irrigation at two locations on each of two kinds of soil*

Depth.	Quantity of water expressed as a percentage of the dry weight of the soil.			
	Newlands Experiment Farm, clay soil.		Prosser Experiment Farm, sandy soil.	
	Location 1.	Location 2.	Location 1.	Location 2.
First foot:				
Before irrigation	14.7	11.0	3.2	4.5
After irrigation	22.6	32.5	10.8	15.2
Second foot:				
Before irrigation	21.4	19.6	5.4	5.3
After irrigation	21.4	31.8	11.8	19.0
Third foot:				
Before irrigation	21.4	17.7	4.2	5.4
After irrigation	21.4	23.8	14.9	12.7

In figure 2 each column of cubes represents a column of soil to the depth of 3 feet, each cube representing 1 foot of soil. The quantity of water in each foot of soil before irrigation is represented by the shaded portion of the cube, and the quantity of water added by irrigation is shown by the black portion. In the first column, on the left, the soil contained before irrigation 9.4 inches of water to the depth of 3 feet, the second column 7.9 inches, the third column 1.91 inches, and the fourth contained 2.4 inches.

The soil represented by column 1 in figure 2 was not in crop when the samples were taken. It was a bare spot in a field of alfalfa where the soil did not take water readily. The irrigation which followed the sampling added only 1.2 inches of water to the soil and that increase was

limited to the surface foot. The soil represented by the second column in the figure was located in the same plat as that shown in column 1 and only 15 feet from it. In this location there was a good stand and a good growth of alfalfa nearly ready to cut. The same irrigation that added 1.2 inches of water to the soil shown in column 1 added 6.5 inches of water to the soil shown in column 2. Both these soils were rich in clay.

The soils of columns 3 and 4 were of a sandy type and were taken from adjacent fields on the Prosser Experiment Farm, Wash. Both fields were carrying a good growth of alfalfa about ready to cut. Irrigation added 3.9 inches of water to the soil shown in column 3 and 5 inches of water to the soil shown in column 4.

It is altogether probable that when these soils were sampled before irrigation the available water supply in the first 3 feet had not been entirely exhausted. But the growth conditions were such that it was deemed advisable to irrigate. It is not always safe nor is it good farming to force the plants to use the last drop of available water.

It is also probable that in the sandy soil of the Prosser Experiment Farm the roots of alfalfa extend below the third foot. Notwithstanding these reservations with respect to the conditions which these figures represent, they afford a comparison as to the relative quantities of subavailable and available water in each location. This comparison is shown in Table V.

The results of a large number of observations covering a wide range of soil types indicate that the capacity of the irrigated soils for holding available water ranges from about 1 inch per foot up to 2 inches per foot, or possibly a little more in exceptional cases.

TABLE V.—*Quantities of water held in the first 3 feet of soil in four locations on two different types of soil*

Classification of water.	Quantity of water expressed in inches of depth.			
	Newlands Experiment Farm, clay soil.		Prosser Experiment Farm, sandy soil.	
	Location 1.	Location 2.	Location 1.	Location 2.
Subavailable	9.4	7.9	1.9	2.4
Available	1.2	6.5	3.9	5.0

THE PENETRATION OF IRRIGATION WATER

It is the aim in applying irrigation water to moisten the soil to the depth of several feet and in doing so to store enough water in this layer of soil to meet the needs of the crop plants for two or three weeks, or until the next irrigation. If this aim is to be realized, it is essential that the water penetrate the soil readily, for it is often not practicable to keep water on the land more than a few hours at a time.

When irrigation water is applied to the land, it penetrates in part by flowing into such cracks in the soil as have been formed by shrinkage and in part by percolating into the minute spaces between the soil particles. Where the soil conditions are favorable, most crop plants develop their roots to the depth of 4 or 5 feet and are thus able to use the water

that may be stored in that zone of the soil by irrigation. It is often observed that certain irrigated lands do not take water readily and that after the surface of the soil has been saturated for several hours or even for two or three days the water has not penetrated downward into the subsoil. This condition is sometimes thought to be due to the existence of a hardpan or plowsole and that deeper penetration of water could be brought about by deeper plowing or subsoiling. It is possible, of course, to break up a dry soil with a plow, and immediately after this has been done irrigation water will flow downward and fill the spaces between the clods. But very often it is found that by the time of the next irrigation, the soil is nearly as compact and impermeable as it was before it was plowed.

While there are many places in irrigated land where a subsurface hardpan occurs and prevents the downward movement of irrigation water, it is also true that some irrigated soils are naturally slow to take water, and this condition is quite independent of any sharply defined impermeable layer.

It is desirable to understand the facts in these cases, for the remedies are different in the different circumstances. If the penetration of water is retarded or prevented by a well-defined hardpan, such as is sometimes formed by limestone known as caliche, this condition may be remedied by shattering the hard layer by deep plowing or by blasting. On the other hand, if the difficulty is due to what is sometimes termed a "colloidal" or "puddled" condition of the soil, deep plowing or blasting is practically useless. The remedy lies in the direction of improving the physical condition of the soil. One who has not had actual experience with irrigation in districts where so-called "hard soils" or "slick spots" occur does not appreciate how resistant to water such soils are. One thinks of a dry soil as thirsting for water, but on these slick spots the water may stand for days and soak down only a few inches.

THE RATE OF WATER PENETRATION

It is possible, though somewhat difficult, to measure the rate at which irrigation water penetrates the soil under field conditions. This may be done by taking a series of soil samples from time to time after the irrigation water is applied. Such investigations have shown that in very permeable sandy soils the water may get down as far as 6 feet in 12 hours. Ordinarily the rate of penetration is much slower. Even in soils that are regarded as readily permeable it may take two or three days for the irrigation water to penetrate to the depth of 6 feet.

The contrast in the rate at which water may penetrate the dry soil may be illustrated by a very simple experiment. If dry pulverized soil is put into a glass tube and water poured on at the upper end, the rate at which the water soaks downward may be observed. The moist soil is much darker colored than the dry soil, so that the advancing line of the penetrating water may be plainly seen and its position may be recorded from time to time by marks on the tube.

The experiment here described illustrates a method of comparing the rate of the penetration of water in two soils, one of which takes water readily while the other takes water slowly. Both soils were taken from the Newlands reclamation project near Fallon, Nev. Both would be classed as sandy loam. When dry and pulverized they resemble each

other so closely as to be almost indistinguishable. In the present experiment these soils were pulverized and passed through a sieve having holes 2 mm. in diameter. The soil was then placed in glass tubes half an inch in diameter and 5 feet in length. The lower end of the tube was fitted with a perforated rubber stopper which was covered with a layer of absorbent cotton. As the soil was poured in, the tube was jarred in such a way as to make the soil settle firmly. The tubes were filled to the 4-foot mark and clamped to a stand in a vertical position. Distilled water was then poured into the top of the tubes to the depth of about 6 inches, and more was added from time to time, as needed. The perforated stoppers in the tubes permitted the escape of air as it was displaced by the descending water. The line of demarcation between the wet and dry soil was very sharp.

Table VI shows the rate of penetration of the water into the soil in the two tubes. In the tube containing soil No. K82 the water penetrated to the depth of 33 inches in three hours, while with soil No. 337 the water had gone down less than 4 inches at the end of the first three hours. In this tube, No. 337, a constant supply of water was kept on the soil for more than a year and the depth of penetration was recorded from time to time. At the expiration of 14 months the water had soaked down to the bottom of the soil column, or 48 inches.

TABLE VI.—*Penetration of water in two samples of dry pulverized soil in glass tubes*

Time elapsed.	Depth of penetration (inches).		
	Soil No. K82.	Soil No. 337.	Rate per day.
1 hour	16.7	2.5	.....
2 hours	25.0	3.2	.....
3 hours	32.7	3.7	.....
4 hours	.....	4.1	.....
5 hours	.....	4.4	.....
6 hours	.....	4.5	.....
1 day	.....	5.6	5.6
10 days	.....	9.3	.41
30 days	.....	12.6	.165
60 days	.....	16.6	.133
90 days	.....	20.0	.113
120 days	.....	23.1	.103
150 days	.....	25.5	.080
12 months	.....	44.0	.086
14 months	.....	48.0	.066

Toward the end of this experiment it became difficult to determine the limit of penetration accurately. Instead of a sharp line of demarcation between the wet soil and the dry, there was a gradual transition of color. Evidently the penetration of water was retarded by conditions in the mass of moist soil in the upper part of the tube rather than by any definitely impermeable area below. It was observed also that the rate of penetration of the water declined rather uniformly as time went on. This has been noted also in other similar experiments.

The outstanding feature of this experiment is that with these two soils, closely similar in physical texture, there is a very great difference

in permeability to water. Such differences are a matter of common observation in the field in irrigated areas and constitute one of the most important distinctions in irrigated soil. The importance of this matter of permeability to water lies in the fact that to function properly in the support of crop plants the soil must act as a reservoir for the storage of water from one irrigation to the next. If the soil is not permeable to water and does not readily absorb water when irrigated, it does not function well in its capacity as a reservoir.

There is another aspect of the case that is also important. Some irrigated soils contain soluble salts, commonly known as alkali, in such quantities that the soil solution is so concentrated as to be toxic to crop plants. When conditions are such that the irrigation water penetrates the soil readily and passes away in the underground drainage, it is not difficult to leach out the excess of soluble salt and thus to reclaim the alkali land. But when the soil is not readily permeable to water, such reclamation becomes difficult or impossible. If conditions are such that the irrigation water soaks down only a foot or two into the soil, it does not carry the salts away. Instead of doing so it evaporates, leaving in the soil not only the salt originally there but also any additional salt which is carried in solution by the irrigation water.

In view of these facts, it is clear that a soil to be used successfully for the production of crops under irrigation must be readily permeable to water, not only that it may serve as a suitable reservoir to hold water for the use of plants but also that any excess of soluble salts may be leached away.

MEASURING THE RATE OF WATER PENETRATION

It is not to be supposed that the rate of water penetration in dry pulverized soil in glass tubes in the laboratory is the same as the rate of penetration of irrigation water in the field. There is, however, reason for believing that the differences in the rate of penetration for different soils as shown in laboratory tests are to be found also in the field and that these differences are in the same direction and substantially of the same degree. Numerous comparisons have been made in the laboratory between soils from different fields and different irrigated regions, and these results appear to accord very well with field experience. This field experience shows clearly that the rate of water penetration varies greatly even in different parts of the same field. An example of this variation is shown in figure 2 and in Table IV.

In making the laboratory tests of water penetration as described above there are certain factors that make for a lack of uniformity. Even when portions of the same soil sample are used in different tubes there are likely to be differences in the degree of fineness of the material used and differences in the way the material settles together in the tube. Table VII shows the differences observed in the rate of water penetration in 5 tubes that were filled from the same sample of soil and given the same quantity of water. These results show that the differences in rate of penetration are relatively slight when compared with those shown by different soils even of closely similar textures, as shown in Table VI.

TABLE VII.—*Penetration of water in each of five tubes containing soil from the same sample*

Time elapsed.	Depth of penetration (inches).					
	Tube 1.	Tube 2.	Tube 3.	Tube 4.	Tube 5.	Mean.
1 hour	3.7	4.3	4.2	3.9	4.5	4.1
2 hours	4.6	5.1	5.1	4.6	5.4	5.0
3 hours	5.0	5.6	5.5	5.0	5.9	5.4
4 hours	5.4	6.0	5.9	5.4	6.3	5.8
5 hours	5.9	6.6	6.5	5.7	6.8	6.3
24 hours	11.6	12.2	11.9	10.2	12.2	11.6

Another example of the differences observed in the rate of water penetration in different soils is shown in figure 3. This figure shows diagrammatically the depth of water penetration in glass tubes containing pulverized dry soil under a fairly constant head of 3 to 4 inches of water. The figures in this diagram show that there are very great differences in the rate of penetration of water in different soils. It is to

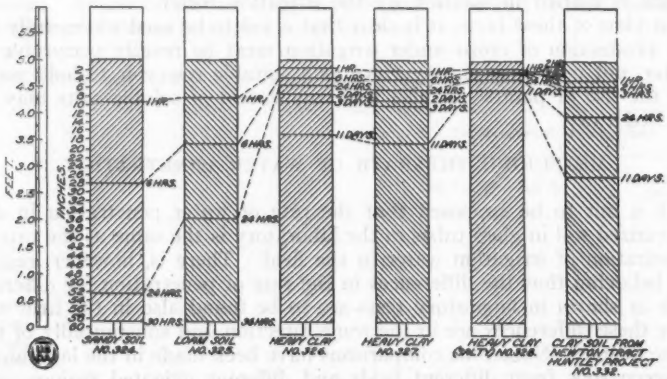

FIG. 3.—Tubes showing rates of moisture penetration in different soils.

be expected that the texture of the soil has an important bearing on the rate of water penetration. This is shown by the more rapid penetration in the sandy soil (No. 324) and the loam soil (No. 325) than in the clay soils of the other tubes.

It is not to be inferred, however, that soil texture is the only factor or that it is even the most important factor influencing the rate of water penetration. It has been shown in Table VI that two sandy loam soils which are indistinguishable as to texture show very great differences in the rate of water penetration. Similar differences are shown in the base of a clay soil from the Belle Fourche reclamation project in South Dakota. This Belle Fourche soil is very rich in clay, having been derived from the weathering of Pierre shale. The four samples shown in Table VIII are all from the same locality and of substantially the same texture. One of them (No. 338) was taken from a spot which had been subjected to the action of seepage water rich in alkaline salts. The other samples were from places that had been watered only by rainfall or irrigated with water in which the proportion of alkaline salts was low as compared with the salts of calcium and magnesium.

It will be seen from the table that the rate of water penetration was six to eight times as fast in the samples that had not been subjected to the action of the alkaline salts as it was in the other sample. The penetration rate on these unaffected clay soils is at first nearly twice as great as that of the sandy loam soil (No. 337) shown in Table VI. Furthermore, the penetration rate was better sustained in the clay soil than in the slowly permeable sandy loam, as is shown by the depth of water penetration in 30 days.

The results of the laboratory experiments with dry pulverized soils in glass tubes afford a means of stating in definite terms what is continually to be observed in the field. They serve to establish two facts which have long been known to irrigation farmers: (1) That some soils absorb water readily while others do not; and (2) that the rate of water absorption is affected by factors other than the texture of the soil.

TABLE VIII.—*Penetration of water in each of four samples of heavy clay soil from the Belle Fourche project in South Dakota*

Time elapsed.	Depth of penetration (inches).			
	Soil No. 338.	Soil No. 339.	Soil No. 340.	Soil No. 341.
1 hour	0.8	4.2	3.4	3.7
6 hours	1.5	9.7	7.6	8.2
1 day	2.3	17.8	14.3	15.3
2 days	2.8	22.2	18.5	19.3
4 days	3.5	26.8	22.5	23.2
6 days	3.8	30.2	25.8	26.0
10 days	.....	34.6	30.1	29.6
30 days	.....	42.1	37.4	38.2

THE PERCOLATION OF IRRIGATION WATER

In the preceding pages reference has been made to the penetration of water into pulverized dry soil. Another situation which has to be dealt with in irrigation practice is the movement of water through a soil already saturated or nearly so. This movement of water through a saturated soil is here designated as percolation. The justification for making a distinction in the present use of these two terms is merely one of convenience. The movement of water into a dry soil may be held to be percolation as truly as the movement of water through a saturated soil. In the first case, the moving water partially or completely displaces air, and in the second case it displaces the water already present.

It is a matter of convenience, however, to distinguish the two conditions by specific terms. In the application of irrigation water to a field the purpose ordinarily is to restock the soil reservoir with water for the use of crop plants. In this process the chief concern is that the water applied to the surface of the field shall enter the soil promptly and be held within the root zone for subsequent use by crop plants.

There are situations which occur not infrequently in irrigated lands where the movement of water through a saturated soil has to be considered as a special problem, and the factors which influence this movement need to be understood. When the water that is held in the soil contains so much dissolved salt as to be injurious to plant growth, it

becomes necessary to displace it by applying fresh water to the surface of the soil. This process, which is known as leaching, is commonly resorted to in the reclamation of saline soils.

The reclamation of saline soils by leaching is possible where the fresh water applied on the surface can percolate readily into the soil and where it is possible for the salty water already present in the soil to move downward into the subsoil or laterally to drainage channels. It is, consequently, a matter of importance to understand the conditions that influence the percolation of water through the soil in dealing with the problem of reclaiming saline soils.

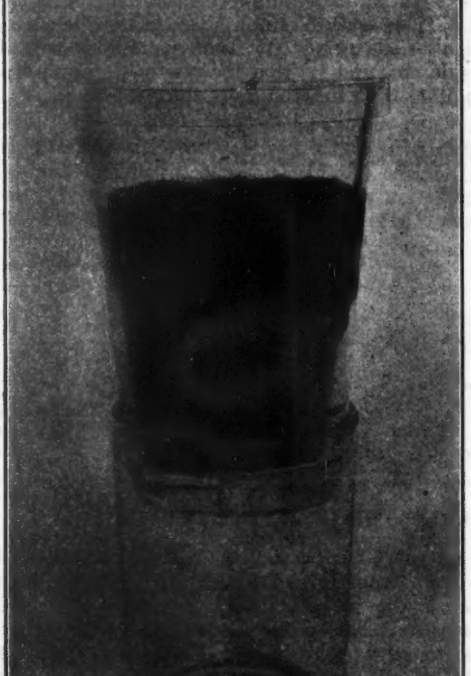

FIG. 4.—Glass used for soil leaching and permeability experiments.

On the other hand, one of the ways that irrigated soils become saline is through the percolation into them of salt-bearing water. The evaporation of such water from the soil leaves the salt behind to be redissolved in succeeding waters. In order to understand the conditions that influence the rate of movement of percolating waters through the soil, it is necessary to be able to measure the rate of movement. This measurement of the movement of percolating water under field conditions is not less difficult than measuring the rate of the penetration of water into the dry soil.

A simple case of the movement of water through a moist or saturated soil may be described as an example of percolation. Let it be assumed that an irrigated field has an underground water table not far below the surface and that the field is provided with a drainage system that affords an outlet for the surplus water. When such a field is irrigated the water applied to the surface of the ground soaks downward and displaces some of the water already present in the soil, and the discharge from the drainage system is correspondingly augmented. It is possible to demonstrate that the water discharged into the drainage system has been displaced from the soil and that it is not the water just put on by irrigation.

This may be done by means of chemical analyses of the two waters. By this means the quantity and character of the substances dissolved in the water may be determined and the identity of the water may be established.

While it is possible by the means indicated above to demonstrate that the percolation of irrigation water proceeds by displacement, it is not a simple matter to determine the rate of this displacement under field conditions. The rate of displacement differs greatly in different parts of the same field because of differences in the texture or structure of the soil, and there is also some mixture of the water and some diffusion of the dissolved material from each water to the other.

Something as to factors that influence the percolation of water through the soil may be learned in the laboratory by the use of the simple device illustrated in figure 4. This consists of a glass pot with a small hole drilled through the bottom to provide drainage. The pot shown in the figure is 3¼ inches across the top and 4½ inches high. It will hold conveniently 300 gm. of soil, leaving space for as much as 100 cc. of water at the top. The loss of soil through the drainage hole may be prevented by placing a small filter paper in the bottom of the pot before putting in the soil. The leaching pot may be set into an ordinary drinking glass to collect the percolate and may be covered with a Petri dish to prevent evaporation from the moist soil.

This apparatus is useful not only for measuring the percolation rate of soils but for investigating the changes that take place in the character of the soil solution during the process of leaching. It is possible also with this apparatus to determine the relative water-holding capacities of different soils, though the water-holding capacity shown in this way is usually much higher than that shown by the same soil under field conditions.

The percolation rate in cubic centimeters per minute as determined in the laboratory by means of the apparatus described above using several different types of soil was as follows: Soil sample No. 326, 0.049; No. 338, 0.100; No. 325, 0.273; No. 324, 0.353; No. 340, 0.506; No. K82, 0.560; No. 339, 0.701; No. K90, 2.109.

The rates of percolation given represent the mean of several observations. A quantitative expression of the percolation rate with two different soils is shown in figure 5.

With soil No. 324, which showed a percolation rate of 0.353 cc. per minute, the discharge for 12 hours would be 254 cc. With soil No. 326, having a percolation rate of 0.049 cc. per minute, the discharge in 12 hours would be only 35.6 cc. A comparison of the percolation rates shown by these two soils with the rate of water penetration shown by the same soils in figure 3 would indicate that the factors that influence the movement of water into a dry soil tend also to influence in the same way the movement of water through a saturated soil.

FACTORS INFLUENCING THE PERCOLATION RATE

It can not be doubted that such factors as the texture of the soil and its structure[5] have a large part in determining the rate of percolation. In fact, if the meaning of the term "structure" is made broad enough it

[5] As here used the phrase "texture of the soil" refers to the composition of the soil as determined by mechanical analysis or to the sizes of the particles composing it. The word "structure" refers to the arrangement of the soil particles in relation to each other, as in the formation of granules or of larger aggregates and in the development of shrinkage cracks on drying.

might include most of the factors that influence percolation rate. The relationship of soil texture to water percolation is too obvious to require much elaboration. When the soil is composed chiefly of large particles the interstitial spaces are correspondingly large and free movement of water is possible. When the soil is composed largely of small particles, the interstitial spaces are much smaller and the movement of water is consequently retarded. The water relations of the soil may be more easily explained and understood by recognizing three main classes of soil material: (1) Sand, (2) clay, and (3) soluble salts.

The class designated as sand may be taken to include all material of whatever size that is crystalline and nearly or quite insoluble in water. The class designated as clay includes the noncrystalline material, also nearly or quite insoluble in water but differing from the sand in that it is very much more finely divided. The soluble salts are mostly crystallized when dry and dissolved or dissociated when wet. In this classification of the soil material the matter of the size of the particles is not

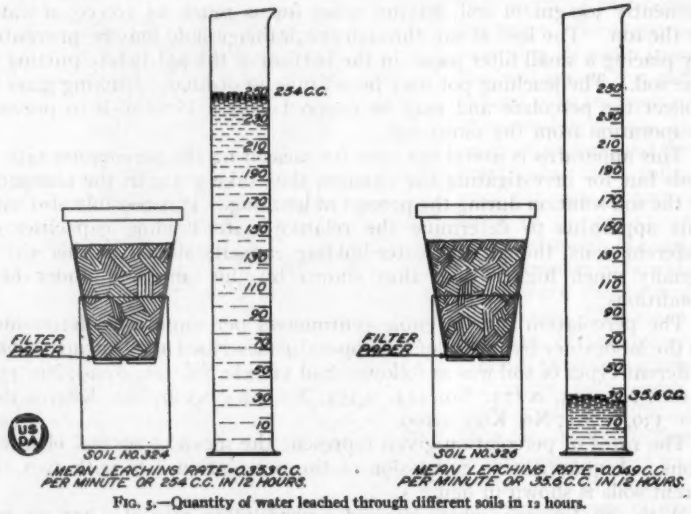
254 C.C.
FILTER PAPER
SOIL NO. 324
MEAN LEACHING RATE = 0.353 C.C. PER MINUTE OR 254 C.C. IN 12 HOURS.
FILTER PAPER
35.6 C.C.
SOIL NO. 326
MEAN LEACHING RATE = 0.049 C.C. PER MINUTE OR 35.6 C.C. IN 12 HOURS.

FIG. 5.—Quantity of water leached through different soils in 12 hours.

emphasized. The crystals, particles, or aggregates may be larger or smaller. The distinctions are made on the basis of the reactions with water.

With respect to these reactions with water, the material classed as sand is regarded as nearly or quite inert. The clay is definitely reactive in that though not soluble in water certain of its constituents may enter into reactions with substances dissolved in the water. The soluble salts are more completely reactive than the clay. They pass into solution and dissociate. They move freely with the movement of water in the soil and even move somewhat by diffusion independently of the movement of the water.

Of the three classes of soil material just described, the clay exercises the most important influence on the movement of water through the soil. The extent and character of this influence varies greatly, depending upon the physical properties of the clay rather than upon the quantity in proportion to the total soil mass. The physical properties of the clay are

in turn largely influenced by its chemical composition, and its chemical composition is largely influenced by the character of the salts dissolved in the soil solution.

Thus it is possible to modify very greatly the rate of water movement through the soil under a given set of conditions by changing the character of the salts dissolved in the soil solution. There is abundant evidence bearing on this point which is well known to all investigators of irrigated soils and to many practical irrigators (*6*, *16*).

The crux of the matter appears to be that clay in the presence of water containing dissolved salts participates in chemical reactions by which exchanges may take place between certain elements combined with the clay and other elements dissolved or dissociated in the water. As a result of these exchange reactions the chemical composition of the clay is altered and in consequence its physical properties also. It is to be noted that the changes in the physical properties of the clay appear to be disproportionately large as compared with the changes in chemical composition resulting from these exchange reactions.

The manifestation of the changes that may take place in the physical properties of clay are not confined to its effect on the movement of water through it. It is shown also in the behavior of the soil on drying and in that complex of properties known as plasticity.

From the above observations it seems safe to conclude that the most important factor influencing the rate of percolation in soil is to be found in the clay portion and also that the percolation rate is determined by the physical condition of the clay rather than by its relative quantity in in the soil.

THE SOIL SOLUTION

It will be apparent from the foregoing statements that the movement of water into or through the soil of an irrigated field is largely influenced by the character of the material in solution in that water. This relationship between the character of the salts in the soil solution and the permeability of the soil is an aspect of the so-called alkali problem that has not been extensively investigated. By far the larger part of the investigations concerning alkali troubles have been concerned with the realtionships between the crop plants and the soil solution.

It is fairly well recognized that when the quantity of dissolved material in the soil solution becomes excessive, crop plants are injured. There is no definite agreement as to what proportions of dissolved material in the soil solution are to be regarded as excessive. In fact, it has been so difficult as to be almost impossible to determine what may be called the critical concentrations of salts in the soil solution. Numerous investigations have been made to determine the toxic limit of solutions with plants grown in water cultures, but the translation of these results into terms of the concentration of the soil solution has not been satisfactory.

The direct determination of the quantity or of the character of the material dissolved in the soil solution is rendered difficult by the fact that it has not been practicable to obtain samples of this solution as it exists in the soil under such conditions as make it available to the plant roots. In other words, it is very difficult to extract water from the soil when the water content is no higher than what may be regarded as optimum for plant growth.

In ordinary investigational work where the salt content of the soil solution is the subject, it is customary to treat a sample of the soil with a large quantity of water and then filter off a part of the water for examination. Some investigators use 5 parts by weight of water to 1 part of soil. Others use 10 parts of water and still others use 20 parts of water to 1 part of soil. There are also some differences of methods as to the length of time the water is left in contact with the soil samples and as to the extent to which the mixture of soil and water is agitated.

It is assumed that the quantity of water used is adequate to dissolve all of the readily soluble material in the soil. An examination of an aliquot part of the water used in treating the soil sample is then made, and the result of this examination multiplied by the appropriate factor gives the quantities of the dissolved materials in terms of the dry weight of the soil. Thus the salt content of irrigated soils is usually given in terms of the percentage of the dry soil rather than as a percentage of the soil solution. It is obviously not practicable to attempt to state the salt content in terms of the soil solution, for two reasons: (1) Because the quantity of the soil solution and consequently its concentration changes from day to day as water is lost by evaporation or added by rainfall or irrigation, and (2) because there is reason for believing that the quantity of material in solution is affected by the quantity of water present. It is largely because of this second reason that investigators hesitate to express the results of their soil analyses in terms of concentration of the soil solution, even when the water content of the soil has been determined.

A single example will serve to show the range in concentration of the soil solution if it is assumed that the salt content of the soil is all dissolved in the soil solution. Where the salt content of the soil is 0.5 per cent and the moisture content is 25 per cent it might be assumed that the salt content of the soil solution would be 2 per cent. On the other hand, if the salt content is 0.5 per cent and the moisture content is 10 per cent then the salt content of the soil solution would be 5 per cent.

It is the consensus of opinion among investigators that the roots of ordinary crop plants can not tolerate concentrations of mixed salts in solution much above 1.5 per cent. Notwithstanding this, many instances are reported of crop plants making fair growth in soils which show by analysis as much as 0.5 per cent of salt to the dry weight of the soil and where the moisture content frequently falls as low as 15 per cent.

Such observations have led to the conclusion that when the soil solution becomes very concentrated through the loss of water by evaporation, some of the salt may be reabsorbed in some way by the soil.

EXTRACTION OF THE SOIL SOLUTION

While it is difficult to obtain a sample of the soil solution when the water content of the soil is at or near the wilting point, it is possible by the use of a centrifuge to obtain a sample when the water content is up to or just above the optimum for plant growth. The centrifuge used in the experiment here described was one designed by Briggs and McLane for use in determining the moisture equivalent of soils (*2*). The machine used differed from the one described in the publication cited in that it was equipped with an outer casing which serves to collect the water that is thrown out of the soil during the run.[1]

[1] The writer is indebted to J. W. McLane for his cooperation in making these solution extractions.

In making these solution extractions the dry soil was placed in the centrifuge cups and then carefully moistened to a point just below saturation. It was left in this condition overnight, protected from evaporation, and then centrifuged. The solution extracted represented that part of the soil solution that is above the limit of the moisture equivalent and below the limit of saturation. The moist soil was weighed both before and after centrifuging, and the dry weight was obtained later. From these figures the percentage of moisture in the soil was determined before and after the run, and it was assumed that the sample of the solution extracted represented a moisture condition midway between the two. The salt content of the extracted solution was determined by means of the electrolytic bridge. Table IX shows the salt content of the solution extracted from four samples of soil.

TABLE IX.—*Salt content of the soil solutions extracted by the centrifuge process from four samples of soil*

Sample No.	Percentage of solution to soil.[a]	Salt content (per cent).	
		Of solution.	Of soil (indicated).
384	33	1.020	0.337
385	36	.050	.018
386	33	.062	.020
385a [b]	30	2.200	.660

[a] This is the midway figure between the percentage of moisture in the sample before the run and the percentage after the run.

[b] Sample 385a was a duplicate of 385 to which approximately 0.6 per cent NaCl was added before the solution extract was made.

Another method of extracting a sample of the soil solution has been used in the laboratory by the writer. It has the advantage of not requiring the use of the centrifuge. By this method a portion of the soil solution is obtained by displacement. A leaching pot, such as is shown in figure 4, is used for this purpose. After placing a small filter paper in the pot, a sample of 300 gm. of dry soil is poured in a little at a time and enough distilled water is added with each portion of the soil sample to moisten just below the saturation point. The pot is then covered to prevent loss of water by evaporation and allowed to stand for 24 hours to reach a condition of approximate equilibrium. It is then weighed to determine the moisture content.

The quantity of soil used will usually hold from 90 cc. to 150 cc. of water. It has been found that by adding from 25 cc. to 50 cc. to the surface of the soil in the pot this added water will displace approximately an equal quantity which leaches out from below. A test of successive fractions of the percolate has shown that its salt content remains fairly constant until the larger part of the original soil solution has been displaced.

The salt content of the soil solution obtained by this method of displacement from samples of the same soils used in the centrifuge test is shown in Table X, together with the computed salt content of the soil. The moisture percentage shown in the table is the result obtained by weighing the moist soil just before leaching.

TABLE X.—*Salt content of the soil solutions obtained by displacement from four samples of soil*

Sample No.	Percentage of solution to soil.	Salt content of solution.	Indicated salt content of soil.
		Per cent.	*Per cent.*
384	55	0.595	0.327
385	47	.059	.028
386	47	.070	.033
385a	46	1.510	.694

The samples of the soil solution obtained either by the centrifuge or by displacement may be considered as representing a condition when the soil contains an ample supply of water for plant growth. A number of investigators have proposed methods of obtaining samples of the soil solution when the moisture content is at or just below what is considered as optimum for plant growth, but none of these methods has as yet come into general use in work with irrigated soils.[7]

In view of the fact that most of the investigational work concerning the salt content of soil is based on results obtained by treating the soil sample with quantities of water that supersaturate it, similar treatments were made on portions of the same samples that were used in the experiments just described.

In each extraction 100 gm. of soil were used. For one set this soil was treated with 100 cc. of water, for the next 250 cc. of water, for the third 500 cc. of water, and for the fourth 1 litre of water. The wetted samples were held for 24 hours and were shaken repeatedly. A part of the water was then filtered off and tested for total salts. The results of these tests together with those made on the centrifuge and displacement extracts are shown in Table XI.

TABLE XI.—*Salt content of the solution and the indicated salt content of the soil when the soil solution was variously diluted*

Sample No.	Percentage of solution to soil.	Salt content of solution.	Indicated salt content of soil.
		Per cent.	*Per cent.*
384	33	1.020	0.337
	55	.595	.327
	100	.287	.287
	250	.127	.318
	500	.065	.325
	1,000	.030	.300
385	36	.050	.018
	47	.059	.028
	100	.038	.038
	250	.016	.040
	500	.011	.055
	1,000	.007	.070

[7] The following papers are among the more recent contributions to the subject of extracting the soil solution and each contains citations of earlier work.

PARKER, F. W.: METHODS OF STUDYING THE CONCENTRATION AND COMPOSITION OF THE SOIL SOLUTION (*14*). BURGESS, Paul S.: THE SOIL SOLUTION, EXTRACTED BY LIPMAN'S DIRECT PRESSURE METHOD, COMPARED WITH 1:5 WATER EXTRACTS (*5*). BURD, John S., and MARTIN, J. C.: WATER DISPLACEMENT OF SOILS AND THE SOIL SOLUTION (*4*). TULAIKOV, N. M., and KUSMIN, M. S.: ON THE QUESTION OF OBTAINING THE SOIL SOLUTION (*19*).

TABLE XI.—*Salt content of the solution and the indicated salt content of the soil when the soil solution was variously diluted*—Continued.

Sample No.	Percentage of solution to soil.	Salt content of solution.	Indicated salt content of soil.
		Per cent.	*Per cent.*
386	33	.062	.020
	47	.070	.033
	100	.035	.035
	250	.019	.048
	500	.012	.061
	1,000	.008	.080
385a	30	2.200	.660
	46	1.510	.694
	100	.665	.665
	250	.262	.655
	500	.130	.650
	1,000	.066	.660

The outstanding features of Table XI are that these soils not only differ greatly in their percentages of soluble material but they differ also with respect to the solubility of that material.

In the case of soil No. 384 the indicated salt content is substantially the same when computed from the centrifuge extract as when computed from the extracts made with large quantities of water. The same is true with soil No. 385a.

With the other two samples, the results are different. With them the indicated salt content of the soil is very much higher when an excess of water is used than when the solution is nearer the normal of field conditions.

These examples are given here to show why it is that investigators hesitate to estimate the concentration of the soil solution from the results they obtain by testing dilute water extracts of the soil.

COMPOSITION OF THE SOIL SOLUTION

Most investigators who are working with solutions obtained from irrigated soils do not attempt to identify all of the substances contained in these solutions. Many of the dissolved materials occur in very minute quantities, and it is probable that they do not have much effect either on the soil or on the plants. There is a wide diversity in the methods used by different workers in the examinations of soil solutions, a term which is here used to include not only the water extracts from soil samples but irrigation and drainage waters as well.

Even in estimating the total quantity of dissolved material there are differences of method. A few of the methods in general use may be listed and briefly described as follows:

(1) A measured quantity of the solution is evaporated to dryness over a steam bath and then dried to constant weight in an oven at a temperature slightly above the boiling point of water; the dried residue is weighed and reported as total dissolved solids in terms of percentage of the original solution or in parts per million.

(2) The same as No. 1 except that the residue after being weighed is heated to low redness to volatilize the organic matter and then weighed again. The loss in weight from heating is then reported as organic matter, and the final residue is reported as total salts.

(3) The electrical conductivity of the solution is measured by the use of a Wheatstone bridge. The bridge reading may be converted in terms of percentage salt content by the use of a calibration table.

(4) A fairly complete analysis may be made, determining quantitatively each of the constituents found to be present and the sum of these reported as the total salts.

(5) A few of the more important acids may be determined volumetrically and these results calculated to their equivalents as salts of sodium, added together, and reported as total salts. To do so involves assumptions that may be misleading. All that is known concerning the composition may be given quite as clearly by reporting the quantities of the various elements or ions that have been identified.

The various constituents of the soil solution are usually reported as parts per million. It is convenient to remember that parts per million may be converted into parts per hundred or percentage by moving the decimal point four places to the left, e. g., 12,000 parts per million equals 1.2 per cent. Likewise, where there is occasion to convert parts per million into pounds per acre-foot of water or of soil, it may be remembered that an acre-foot of water weighs approximately 2.75 million pounds and an acre-foot of soil weighs about 4 million pounds. Thus, if a sample of water is found to carry 730 parts per million of salt that would be equivalent to 1 ton of salt per acre-foot of water.

There are in addition a number of modifications of these methods, but these examples serve to show something of the diversity of methods that are in general use for estimating the salt content of the soil solution. The material dissolved in the soil solution is assumed to exist as salts in equilibrium as to acids and bases. The methods of chemical analysis do not permit the identification of these salts as such, but only of the acid or basic radical or ion. Thus, we may determine with a fair degree of accuracy the quantity of chlorin (Cl), of sulphate (SO_4), or nitrate (NO_3) in a solution and also the calcium (Ca), the magnesium (Mg), or even the sodium (Na), but we can not with certainty know how these exist in the solution with reference to each other. It is questionable whether it is desirable to attempt to state the composition of soil solution or of irrigation and drainage waters in terms of combined salts.

IMPORTANT CONSTITUENTS OF THE SOIL SOLUTION

The term soil solution as here used is intended to include not only the solution as it exists in the soil of an irrigated field but also the accumulated underground water or drainage and the water used for irrigation. In other words, water that has been in contact with soil is here termed soil solution. It is not intended to include as a part of the soil solution any of the inert suspended matter that may be removed by careful filtering.

The more important constituents of the soil solution as it exists in relation to irrigated soils may be enumerated as follows: The bases are calcium, magnesium, sodium, and potassium. The acids are sulphate (SO_4), chlorin (Cl), bicarbonate (HCO_3), carbonate (CO_3), nitrate (NO_3), phosphate (PO_4), and silica (SiO_3). Other bases, such as manganese, iron, and aluminum, are sometimes found in soil solutions, and some other acids, particularly organic acids, also occur, but these are not often separately identified.

There is some diversity in the methods used for quantitative determination of the constituents of the soil solution. It is not the purpose here to give a detailed description of these methods, but merely to give an account of them that may serve as a basis for a later discussion of soil reactions in which the character of the soil solution, as determined by these methods, plays an important part.

CALCIUM

The fact that calcium forms an insoluble compound when combined with oxalic acid is the basis of one group of calcium determinations. The precipitated calcium oxalate may be separated by filtering and the quantity of calcium weighed as the oxid after burning or the quantity of combined oxalic acid determined volumetrically by the use of potassium permanganate.

Another reaction of calcium is also used to some extent. This is its reaction with soap. Both calcium and magnesium form insoluble compounds with soap, and consequently it is possible to estimate the quantity of calcium and magnesium there is in a solution by using a standard soap solution added a little at a time. The solution being tested is shaken in a bottle after each addition of the soap solution. When all the calcium and magnesium have been precipitated by the soap, the solution quickly forms a lather when shaken.

MAGNESIUM

The gravimetric determination of magnesium is based on the fact that this base forms an insoluble precipitate with phosphoric acid. When all the calcium has been precipitated from a solution by the use of oxalic acid, as mentioned above, the addition of sodium phosphate results in the formation of magnesium phosphate which may be filtered off and weighed.

The magnesium content of a solution may be estimated by first determining the total content of calcium and magnesium, as with the soap solution; the calcium content may then be determined on another sample of the solution and the magnesium estimated by difference.

SODIUM AND POTASSIUM

The accurate gravimetric determination of sodium and potassium in solution is rendered difficult by the fact that most of the compounds of these bases are soluble. The usual method of procedure is to separate out the other bases and also remove all the sulphate from the solution, replacing it with chlorin to combine with the sodium and potassium and then evaporate to dryness and weigh the residue as the chlorids of the two bases. If it is desired to determine the potassium separately from the sodium the residue is redissolved and the potassium is precipitated with platinic chlorid. Many water analysts do not undertake to make direct determinations of sodium and potassium because the processes are difficult and tedious. Having determined the total salts or the totals of the acids and of the calcium and magnesium in the solution they estimate the sodium by difference or by the requirement of the acids after eliminating the quantity of the acids required to combine with the calcium and magnesium.

SULPHATE

The sulphate content of the solution may be determined by the addition to it of an excess of barium chlorid. This results in the formation of the insoluble barium sulphate which may be filtered off and weighed. The freshly precipitated barium sulphate forms a white turbidity in the solution, so that a fair estimate of the quantity of sulphate may be made by comparing this turbidity with known standards.

CHLORIN

Chlorin is determined by titration with a standard solution of silver nitrate, using potassium chromate as an indicator. The first reaction is the formation of insoluble silver chlorid. When all the chlorin has been combined the silver reacts with the chromate to produce a change of color.

CARBONATE AND BICARBONATE

The conventional method for the determination of these weak acids is to titrate the solution with a standard solution of a stronger acid, such as sulphuric, using phenolphthalein as the indicator for carbonate and methyl orange as the indicator for bicarbonate. The reaction involved in these titrations and the interpretation of their results call for a more detailed statement than has been made concerning the other constituents of the soil solution. This may be justified in part because the carbonates are generally regarded as the most troublesome substances in the solution, both in relation to the soil and the plants, and partly because of some uncertainty as to the significance of the results of the titrations.

In the first place, it should be kept in mind that the carbonate-bicarbonate complex is very unstable. That is to say, a change in the quantity of carbon dioxid in the solution immediately causes a change in the proportion of carbonate to bicarbonate. This change may be illustrated by the following equation:

$$(1) \qquad Na_2CO_3 + HO_2 + CO_2 = 2NaHCO_3$$

This equation indicates the reaction that takes place when carbon dioxid is added to a solution of sodium carbonate in water, which reaction is in the direction of converting the carbonate to the bicarbonate. The removal of carbon dioxid from the solution, which may be done by aeration or boiling, causes the reaction to take place in the other direction or to change the bicarbonate into the carbonate. The quantity of carbon dioxid in solution is extremely variable, depending upon conditions which are constantly changing, so that there is comparatively little significance to be attached to the distinction between carbonates and bicarbonates in irrigation and drainage waters.

In making a titration for carbonate in a solution, a few drops of phenolphthalein is first added. If the solution takes on a pink or rose color this is assumed to indicate the presence of the normal carbonate (CO_3), and a solution of standard sulphuric acid is added until the color disappears.

The course of the reaction may be illustrated as follows:

$$(2) \qquad 2Na_2CO_3 + H_2SO_4 = Na_2SO_4 + 2NaHCO_3$$

This might be taken to indicate that the pink color of the phenolphthalein indicates the presence of the carbonate radical, but there is another explanation that appears to serve better. Sodium carbonate is an example of a strong base united with a weak acid. When this salt is dissolved in water it is partially dissociated and hydrolized as follows:

$$(3) \qquad Na_2CO_3 + H_2O = NaOH + NaHCO_3$$

It is not assumed that this reaction is complete, but rather that in a solution of sodium carbonate there exists a certain quantity of free hydroxyl ions (OH) and that these cause the phenolphthalein to show pink

color. According to this explanation the reactions of the carbonate titration would be indicated thus:

$$2NaOH + H_2SO_4 = Na_2SO_4 + 2H_2O \quad (4)$$

It is assumed that only a part of the sodium carbonate is dissociated and hydrolized in the orginal solution, but that as titration proceeds these reactions go on until the supply of the dissolved carbonate is exhausted. The acid used in titrating the solution until the phenolphthalein color disappears accounts for only one half the original quantity of carbonate. According to the equation (2), the first step of the titration reaction is to form sodium sulphate and sodium bicarbonate. In making carbonate titration the burette reading for the phenolphthalein reaction is doubled before computing the carbonate content of the solution.

Upon completing the titration with phenolphthalein, a few drops of methyl orange is added to the solution and the addition of acid continued until the solution changes color from lemon yellow to orange. By this titration the total quantity of bicarbonate in the solution is determined. The reaction may be indicated as follows:

$$2NaHCO_3 + H_2SO_4 = Na_2SO_4 + H_2O + CO_2 \quad (5)$$

As has been indicated above, the bicarbonate content of the original solution has been increased when carbonate was present through the conversion of the carbonate to the bicarbonate. Thus in computing the carbonate and bicarbonate equivalents of the acid used in titrating a solution it is necessary to deduct from the burette reading for the methyl orange titration the equivalent of the burette reading for the phenolphthalein titration. The remainder may be taken as the acid equivalent of the bicarbonate originally in the solution.

The correct interpretation of the results of the titrations for carbonates and carbonates in soil solutions is beset with still other complications. One of these has to do with the fact that the silicate radical (SiO_3) when it occurs in solution gives the same color reaction with phenolphthalein as the carbonate. This may lead to some confusion in dealing with certain strongly alkaline solutions. Not only does it give too high values for carbonates but it upsets the determination of bicarbonate also. From what has been said above concerning the titration for carbonate it will be evident that if a solution contained carbonate but no bicarbonate its complete titration would require equal quantities of acid to neutralize the phenolphthalein and the methyl orange. With a solution containing silicate this is not the case. It takes much more acid to neutralize the phenolphthalein color than it does to complete the titration with methyl orange. It sometimes happens in laboratory work that solutions are obtained that show an abnormally high proportion of carbonate as compared with the bicarbonate. With such solutions it is advisable to test for silica.

Another source of error in determining the carbonate-bicarbonate constituents of solutions has to do with the evolution or escape of carbon dioxid between the time the sample is taken and the time the titration is made. On one hand, if the solution contains organic matter either suspended or dissolved this may be broken down with the consequent liberation of carbon dioxid. If the solution is stored in a closed container this carbon dioxid may combine with the normal carbonate to form

bicarbonate. On the other hand, it has been observed that certain samples of underground water when first taken show no phenolphthalein reaction, but if these are allowed to stand for a few hours exposed to the air they give a strong reaction for normal carbonate.

One of the practical difficulties in titrating soil solutions is encountered when the solution is strongly colored or turbid, due to the presence of dissolved or suspended organic matter. With such solutions the end point of the indicator reaction is not easy to see. It has been found that this difficulty may be overcome by placing the solution to be titrated in a bottle which can be corked and shaken after each addition of acid. The shaking causes the formation of foam which persists at least momentarily after the shaking stops. The indicator colors can be seen in this foam quite as sharply as in a clear solution.[8]

The discussion of this subject of the determination of the carbonate-bicarbonate constituents of the soil solution may be summarized by pointing out that these determinations are at least difficult to interpret. It is regrettable that this is so because these constituents are known to be closely associated with some of the most important reactions that take place in irrigated soils. They are also regarded as highly toxic to crop plants.

NITRATE

The nitrate content of the solution is determined by the use of phenol-disulphonic acid with which the nitrate reacts to produce a yellow color when the solution is made alkaline, as with ammonia. A comparison of the unknown solution with solutions of known strength affords a basis for estimating the nitrate content.

SILICA

Silica in solution may be precipitated by evaporating to dryness, acidulating with hydrochloric acid, evaporating again, and finally taking up the soluble residue with dilute acid. The silica may be separated from the other constituents of the solution because it does not redissolve in an acid solution after being dried.

In making a silica determination with soil solutions it is essential to free the solution of all suspended matter. In the water extracts of irrigated soils and in some turbid irrigation waters silica is an important constituent of the suspended matter. In this condition it is not, however, a part of the true solution.

STATING THE RESULTS OF ANALYSES

From what has been said on the preceding pages it is obvious that in reporting the results of analyses of samples of the soil solution or of irrigation or drainage waters one can not with certainty report the salts as such. The analysis permits the identification of certain elements or ions, but gives no clue as to how these are combined if at all. Indeed such evidence as we have would indicate that in the dilutions with which we commonly have to deal, these constituents exist largely in a dissociated condition.

[8] The writer is indebted to J. F. Breazeale for this detail of technique.

It is doubtful if any useful purpose is served by reporting such analyses in terms of combined salts. The character of the solution may be indicated quite as clearly by reporting the quantities of the constituents identified as by reporting the theoretical combinations which are conjectured. Furthermore, where the report includes only the elements or ions that have been identified it is less subject to misinterpretation than when it is given in terms of combined salts of which only one element or radical has been determined. The results of the analyses of certain underground waters are given in Table XII stated in parts per million. The figures in this table give all the facts that were actually determined in making the analyses.

TABLE XII.—*Composition of certain underground waters*

Sample No.[a]	Total Solids.	Constituents (parts per million).					
		Ca.	Mg.	HCO_3.	Cl.	SO_4.	NO_3.
1	1,614	134	24	249	642	211	.....
2	1,453	203	28	163	501	259	19
3	534	108	16	236	115	127	.....
4	3,570	80	172	[b] 279	312	1,920	.....
5	9,142	555	146	504	140	5,896	.....
6	5,400	408	543	549	160	2,700	.....
7	5,864	270	191	432	84	3,427	.....

[a] The following is a description of the water samples:
No. 1, From wells tapping the underflow of the Gila River above Yuma, Ariz.
No. 2, From wells used for irrigation on the south side of the Salt River Valley, Ariz.
No. 3, From wells used for irrigation on the west side of the Salt River Valley, Ariz.
No. 4, From a drain on the Newlands project, Nevada.
No. 5, From a drain on the Shoshone project, Wyoming.
No. 6, From a drain on the Belle Fourche project, South Dakota.
No. 7, From a drain on the Huntley project, Montana.
[b] Includes 48 parts per million normal carbonate. The other samples showed no reaction with phenolphthalein.

Where it is desired to make a comparison between several different samples of water as to the character of their dissolved constituents such comparison is greatly facilitated by stating the constituent in terms of percentage of the total solids. In order not to have too many items for comparison, constituents having similar properties may be combined in the percentage statement. Thus the calcium and magnesium may be taken together and the carbonate and bicarbonate. In view of the fact that the bicarbonate radical (HCO_3) is monovalent while the carbonate radical (CO_3) is bivalent it is customary in combining them in the percentage statement to divide the figure for the bicarbonate by 2 before making the addition.

The combining weights of the bases and acids ordinarily found in irrigation and underground waters are such that the sum of the acids constitutes about two-thirds of the weight of the total solids. As a check on the accuracy of the analytical report, the percentage statement of the results may properly include an item for the total acids. If the figure for this item falls much above 70 or much below 60 the implication is that there has been an error in the work or that some other acid, possibly the nitrate radical, should be looked for.

When the analysis of a water sample includes all the important bases, that is, the sodium and potassium as well as the calcium and magnesium,

the sum of these basic constituents makes up about one-third of the weight of the total solids. Where only the calcium and magnesium have been determined by analysis, the percentage statement of the results indicates approximately at least whether the water is to be classed as "hard" or "soft" with reference to the balance between the two classes of bases.

If the sum of the calcium and magnesium is about 15 per cent of the total solids, it may be assumed that the calcium-sodium ratio is not far from 50–50.

For a discussion of the significance of the calcium-sodium ratio in irrigation waters see Scofield and Headley (*16*).

An example of a report on the quality of certain underground waters is shown in Table XIII. In this table the figures in the column headed "total solids" give the percentage of these to the original solution. The other figures in the table report the constituents that were identified in terms of percentage of the total solids. With this form of report it is less difficult to compare different waters as to the proportion of their important dissolved constituents even though the total quantities of these constituents are very different. It is obvious that the proportion of calcium and magnesium to the sodium must be low in samples 1, 4, 5, and 7. Sample 3 is high in bicarbonate though low in total solids. Samples 1 and 2 are high in chlorids, while samples 4 to 7 are high in sulphates.

TABLE XIII.—*Composition of certain underground waters in which the total solids are stated as percentage of the solution and the important groups of constituents are stated in terms of percentage of the total solids*

Sample No.	Total solids.	Constituents as percentage of total solids.					
		Ca+Mg.	$\frac{CO_3+HCO_3}{2}$.	Cl.	SO_4.	NO_3.	Total acids.
1	0.161	9.8	7.8	39.8	13.1	.....	60.7
2	.145	16.1	6.1	34.8	17.4	1.3	59.6
3	.053	23.2	22.1	21.5	23.8	.....	67.4
4	.357	7.1	3.91	8.7	53.8	.....	66.4
5	.914	7.7	2.8	1.5	64.5	.....	65.2
6	.540	17.6	5.1	3.0	50.0	.....	58.1
7	.586	7.9	3.7	1.4	58.4	.....	63.0

The method of reporting the constituents as percentages of the total dissolved solids or total salts does not permit close or accurate comparisons between different waters because these constituents have different molecular or combining weights. For example, 12 parts per million of magnesium has the same combining value as 20 parts per million of calcium. In the same way with the acids, 48 parts per million of sulphate has the same combining value as 35.5 parts per million of chlorin or 30 parts of carbonate. These differences in molecular or combining weight make it impossible to express the true character of solutions by the percentage method of statement. This method is simple and convenient, but at best it permits only approximate comparisons. Where it is desired to make more accurate comparisons between different waters it is advisable to use a method which takes into account these differences

in the combining or reacting values of the constituents. Such a method has been proposed by Stabler (*17*, *18*) and elaborated by Palmer (*13*) and has been extensively used by water analysts in connection with industrial problems though it has not as yet been used generally in connection with irrigation and drainage investigations. This method of interpreting water analyses is based on the use of what is known as the reaction coefficient for which the symbol r is used. The reaction coefficient of an element or ion is determined by the ratio $\frac{\text{valence}}{\text{atomic weight}}$. These coefficients for the more important radicals found in irrigation waters are given in Table XIV.

TABLE XIV.—*Reaction coefficients for the more important radicals found in irrigation waters*

Positive radicals.	Reaction coefficients.	Negative radicals.	Reaction coefficients.
Calcium (Ca)	0.0499	Carbonate (CO_3)	0.0333
Magnesium (Mg)	.0822	Bicarbonate (HCO_3)	.0164
Sodium (Na)	.0435	Chlorin (Cl)	.0282
Potassium (K)	.0256	Sulphate (SO_4)	.0208
		Nitrate (NO_3)	.0161

The reacting values of the dissolved constituents are determined by multiplying the parts per million by the reaction coefficient and the results obtained are designated by prefixing the symbol r to the symbol for the radical. Thus r Ca is the designation for the reacting value of calcium. The application of the method of reacting values to the statement of water analyses is illustrated in Table XV in which it is used with the results given in Table XII.

The reacting values of the various constituents as given in the table are stated in terms of molecular equivalent units. If the analyses were complete and correct the sum of the reacting values of the bases or positive radicals should equal the sum of the acids or negative radicals. In ordinary analytical work the alkaline bases, sodium and potassium, are not usually determined. In the absence of this determination it is not possible to compute directly the proportions of the earthy bases, calcium and magnesium, to the alkaline bases or the percentage of the earthy bases to the total bases. This is a relationship that appears to be important in view of the known differences in the reactions of the elements of these two groups.

In order to make an estimate of the percentage of the earthy bases to the total bases in the solution as well as to be able to make direct comparisons between different waters it is convenient to compute the reacting values of the constituents into percentages. If it may be assumed that the determinations of the acid constituents are approximately accurate, the sum of the reacting values of the acids may be used as a basis for computing the percentages of the constituents. The results of such computation are given in Table XVI. It is believed that this method of statement of the results of analyses gives a fairly clear picture of the essential features of the solution and also permits a fair comparison of one solution with another.

TABLE XV.—*Reacting values of the constituents of certain underground waters, the composition of which is given in Table XII in parts per million*

Sample No.	r Ca.	r Mg.	r HCO_3.	r Cl.	r SO_4.	r NO_3.	r Acids.
1	6.69	1.97	4.08	18.10	4.39	.....	26.57
2	10.13	2.30	2.67	14.13	5.30	0.31	22.41
3	5.39	1.31	3.87	3.24	2.64	.....	9.75
4	3.99	14.13	[a] 4.57	8.79	39.95	.....	53.31
5	27.70	12.00	8.26	3.95	122.50	.....	134.71
6	20.35	44.60	9.00	4.51	56.20	.....	69.71
7	13.47	15.70	7.08	2.26	71.15	.....	80.49

[a] Includes 1.6 r CO_3.

TABLE XVI.—*Composition of certain underground waters stated as percentages of the sum of the reacting values of the acids from Table XV*

Sample No.	Total soilds.	Percentage of reacting value.						
		r Ca.	r Mg.	r Ca+ r Mg.	r HCO_3.	r Cl.	r SO_4.	r NO_3.
1	0.161	25.2	7.4	32.6	15.3	68.2	16.5	.....
2	.145	45.2	10.3	55.5	11.9	63.1	23.6	1.4
3	.053	55.3	13.3	68.6	39.7	33.2	27.1	.....
4	.357	7.5	26.5	34.0	[a] 8.6	16.5	74.9	.....
5	.914	20.6	8.9	29.5	6.1	2.9	91.0	.....
6	.540	29.2	64.0	93.2	12.9	6.5	80.6	.....
7	.586	16.7	19.5	36.2	8.8	2.8	88.4	.....

[a] Includes 3.0 per cent r CO_3.

THE SOLUBILITY OF SOIL CONSTITUENTS

In dealing with irrigated soils which often contain appreciable quantities of material that is readily soluble in water it is possible to recognize four classes of substances, as follows:

(1) Soluble material, which may be defined as material that is soluble to an extent greater than can be satisfied by the quantity of water in the soil, e. g., the salts of the strong acids with the four principal basic elements and also the carbonates and bicarbonates of the alkali bases. A possible exception in this series is calcium sulphate.

(2) Slightly soluble material, which may be defined as material that is so little soluble that the soil solution is ordinarily saturated with respect to it, e. g., the carbonates of the earthy bases, calcium, and magnesium, and sometimes calcium sulphate.

(3) Replaceable material, which includes the bases, both earthy and alkaline, that are combined with the soil material in such a way that they may pass into solution only if the solution contains an excess of some other base with which the combined bases may exchange, e. g., a soil may be rich in combined calcium and may yield only a trace of this element to treatment to pure water, but when treated with a solution of sodium chlorid it may yield an abundance of calcium.

(4) Insoluble material, which includes the great bulk of the soil. This consists largely of silica either as pure quartz or more commonly as double silicates or compounds of alumina and silica together with one or another of the common earthy or alkaline bases. Some of the double or complex silicates also contain iron and may contain more than one of the bases.

This classification of the soil material, while admittedly an arbitrary one, is useful in that it makes it possible to arrive at a better understanding of the changes that occur in the soil solution as a result of irrigation and leaching and of the reactions that take place between the solution and the

soil. Under field conditions the soil solution is never at rest or in a condition of equilibrium. During the time that irrigation water is being applied the solution is being diluted and is moving downward through the soil. For the remainder of the time it is being concentrated through the loss of water by evaporation and transpiration, and there may be a slight upward movement to replace these losses. In its movement the solution carries its dissolved substances with it. The movement of these dissolved substances by diffusion is probably so slight as to be negligible. For all practical purposes the movement of the dissolved salts in the soil is limited to and determined by the movement of the soil water.[9]

A solution constituent may be precipitated and its further movement arrested in either of two ways. The solution may become concentrated by evaporation to the point of saturation with respect to that constituent, or the constituent, if basic, may take part in an exchange reaction and be withdrawn from solution even though the solution is well below the saturation point with respect to it. It has not been demonstrated definitely that the acid constituents of the soil solution take part in exchange reactions.

There are very pronounced differences in the solubility of the various important constituents of the solution as it exists in irrigated soil. Very little is known as to what these limits are—that is, as to the concentrations at which the precipitation of any given salt takes place in the soil. The precipitation of a salt from solution or, in other words, the limit of solubility may be influenced profoundly by either of two factors. One of these is temperature and the other is the character of the other constituents in solution. The limits of solubility in pure water of the more important constituents of the soil solution in irrigated land are shown in Table XVII. The figures in this table give the limits of solubility in terms of percentage of the water of the solution and also in terms of the reacting values of the elements or ions. These figures show that with most of the salts the limit of solubility increases with the temperature.

TABLE XVII.—*Solubility in water of the earthy and alkaline bases in the presence of the various acids commonly found in the soil solution, expressed as percentage of the solvent and as reacting values* [a]

	Temperature.	Calcium Ca''.		Magnesium Mg''.		Sodium Na'.		Potassium K'.	
		Per cent.	Reacting value.	Per cent.	Reacting value.	Per cent.	Reacting value.	Per cent.	Reacting value.
Carbonate, CO_3''	Cold	0.0013	0.26	0.0106	2.5	7.1	1,340	89.4	12,900
	Hot	.088	17.6	.....	.....	45.4	8,570	156.0	22,600
Bicarbonate, HCO_3'	Cold	.1	20.0	2.21	520	6.9	821	22.4	2,240
	Hot	.....	.....	.....	.....	16.4	1,955	60.0	6,000
Sulphate, SO_4''	Cold	.179	26.3	26.9	4,450	4.8	656	8.5	975
	Hot	.178	26.2	73.8	12,200	42.5	5,900	26.2	3,000
Chlorin, Cl'	Cold	59.5	10,725	52.2	10,950	35.7	6,100	28.5	3,825
	Hot	154	28,000	65.9	13,850	39	6,660	56.6	7,580
Nitrate, NO_3'	Cold	93.1	11,356	200.0	15,620	72.9	8,580	13.3	1,315
	Hot	351.2	42,829	.....	.....	180.0	21,180	247.0	24,400

[a] From Van Nostrand's CHEMICAL ANNUAL, 1913 (20).

[9] The movement of dissolved salts here referred to should not be confused with the movement of ions in the solution which may take place in connection with the absorption by plants. See Breazeale, J. F. (1)

Our information as to the effect on the solubility of one salt of the presence in the solution of another constituent is far from complete. It is well known that carbon dioxid dissolved in water increases the solubility of calcium carbonate except when the solution contains sodium in excess of the strong acids. Likewise it is known that chlorin in solution increases the solubility of calcium sulphate unless the calcium in solution exceeds the equivalent of the carbonate and sulphate ions in the solution, otherwise the solubility of calcium sulphate is decreased. These examples are cited merely to show that in a system as complex as the soil solution it is not possible to state definitely the limits of solubility. Not only is the system complex with respect to its composition but it is never in equilibrium. It is either in the way of being made more dilute by irrigation or rainfall or of being concentrated by evaporation and withal it is participating in those reactions that are continually taking place between the substances in solution and those combined in the soil.

A consideration of the factors influencing the solubility of the soil material can not well be confined to a discussion of the reactions of inorganic acids and bases. The soil of a cultivated field is teeming with organisms including fungi, bacteria, and nematodes, to name only a few of the groups. It contains also the organic residues of plants and of animals in various stages of decomposition. These organisms and the products of the decomposition of the organic matter have a most important bearing on the character of the soil solution in its relation to crop growth. They doubtless have, also, a bearing on the physical condition of the soil and consequently on its permeability to water. But it is not within the scope of the present paper to deal with these organisms or with the subject of organic matter in relation to the condition or productivity of the soil.

There remains to be considered in some detail one other constituent of the soil and of the soil solution which is believed to play a most important rôle in the matter of the movement of water. This is silica. Although silica is the most abundant substance in the soil, we have as yet very little knowledge of it and of the nature of its reactions. Silica, or the oxid of silicon (SiO_2), was first identified by Berzelius in 1823, though its molecular weight was not established definitely until many years later. It occurs in nature in a great variety of forms, sometimes pure, as in quartz or rock crystal, sometimes combined with water, as silicic acid, but more commonly in combination with one or more of the earthy or alkaline bases. It is the most universal cementing material known.

Notwithstanding the fact that silica is not ordinarily recognized as a constituent of the soil solution, it appears to be unquestionable that it exists in and is often abundant in the solution. The fact that it constitutes an important part of the mineral matter of certain plants and that it is utilized by a great variety of small organisms, such as the infusoria in forming their shells or skeletons, justifies the belief that it exists in a soluble form. Furthermore, it is sometimes identified as an important dissolved constituent of the waters of mineral springs and deep wells. Some water analysts hold the view that the silica found in water is to be regarded as suspended matter rather than as a true solute; in other words, that it should be reported as SiO_2 rather than as an acid ion SiO_3. Yet in some cases, at least, the evidence seems conclusive that it may exist as an acid ion. It combines with certain bases to form definite salts. As calcium silicate it is sparingly soluble in water, 95 parts per million.

In combination with the alkali bases, sodium and potassium, it forms salts that are indefinitely soluble in water under certain conditions though soluble only with difficulty after being dried. In solution these salts of silica give a strong alkaline reaction like the carbonates. The combination of water with silica, which is known as silicic acid, H_2SiO_3, is in some ways analogous to the combination of carbon dioxid and water. Both are known as weak acids, but in many respects they are altogether unlike.

From what has just been said it may be inferred that in dealing with silica in its relation to the soil solution one finds much that is unknown and baffling. There appears to be some justification for the view that silica, considered as an acid ion, is chiefly involved in those reactions of replacement or exchange that are known to take place between the soil and the basic constituents of the soil solution. Until the facts are more definitely established it is not possible to do more than to conjecture the nature of these reactions and their relationships to the observed changes in the physical condition of the soil. The known facts are at best extremely fragmentary. We may observe that as a result of treating the soil with a solution of a sodium salt certain reactions take place. Some of the sodium disappears from the solution and equivalent quantities of other bases appear in the solution. If the solution is then replaced as by leaching the soil with pure water, the new solution formed from the contact of the water with the soil gives an alkaline reaction and the soil manifests symptoms which we designate as "colloidal."

These phenomena may be explained by saying that when the solution containing sodium was in contact with the soil some of the sodium of the solution entered into combination with the silica of the soil and replaced from combination other bases; also that the silicate compound resulting from this exchange reaction remains insoluble and inert as long as the solution with which it is in contact contains quantities of the strong acid ions—sulphate, chlorin, or nitrate. Finally, if this solution containing one or more of the strong acid ions be replaced or diluted by pure water then the sodium silicate passes from its previously inert or flocculated condition into a dispersed condition. In this latter condition it exhibits the properties of a colloid in that it may form a hydrosol or a hydrogel. In the condition of a hydrogel it absorbs and holds water, thus making the soil impermeable to the movement of water through it, and when its absorbed water is lost by evaporation the gel cements the soil particles together into solid masses.

It should be clearly understood that the above explanation of the phenomena that may be observed from the treatment of a soil with a solution of a sodium salt is proposed merely as a working hypothesis and not as a statement of facts. The facts remain to be established by further investigation.

In view of what is known it seems probable that a better understanding of the causal relationship between the character of the soil solution and the physical condition of the soil awaits further information concerning those silicates of the soil that lie along the border line of solubility.

EFFECT OF DILUTING THE SOIL SOLUTION

When the soil of an irrigated field contains so much soluble material that the soil solution is too concentrated for normal plant growth, the only practicable remedy is to apply an excess of irrigation water and carry

a part of the salt away by leaching. This can be done of course only where the soil is permeable to water and where the conditions of underdrainage are such that the soil does not become permanently saturated or water-logged.

From this statement of the case, it might be inferred that the reclamation of so-called "alkali land" is not a very serious undertaking. As a matter of fact, such reclamation has been found to be very difficult if not impossible in some cases. On the other hand, there have been many instances where it has been both easy and successful.

It is naturally a matter of a good deal of importance to be able to determine in advance whether a tract of salty land can be reclaimed at a reasonable cost. The cost of providing drainage outlets and of preparing the land for irrigation may be large. If this expense is incurred and it is then found that the land does not become productive as a result of the work done upon it, the investment is lost.

The essential feature of the reclamation of salty land is the dilution of the soil solution. This is done by applying water of low salt content to the surface of the soil, to soak down through, dissolving out the soluble material or displacing the more concentrated soil solution, and then by providing drainage outlets for the salty water where such outlets are needed. In this process of diluting the soil solution in a salty soil the reaction of the soil to the change in the character of the solution is a matter of the greatest importance. It sometimes happens that this reaction is very slight; that is, that the physical character of the soil, particularly as regards its permeability to water, remains practically unchanged. Unfortunately, this is not always true. There are many examples of attempts to reclaim salty soil by leaching that have been given up because when the concentration of the soil solution was reduced the soil became nearly or quite impermeable to the further movement of water through it.

These differences in the reaction of the soil to the dilution of its solution have led to corresponding differences of opinion as to the possibilities of reclaiming salty land. In some regions one finds that irrigation farmers are confident that such land can be reclaimed if adequate drainage is provided and the land is thoroughly irrigated. In other regions one finds an equally firm conviction that when a tract of land has once become salty it is permanently ruined.

The fundamental reason for these observed differences in the reaction of the soil has not been clearly understood, but more light has been obtained as a result of recent investigations. The reactions that take place in the field may now be duplicated in the laboratory. When this is done it is found that the differences in soil reaction as the soil solution is diluted are associated with differences in the character of the material in the soil solution.

Where investigators working with salty soils have identified only the acids in the solution, they have observed that the reaction toward impermeability has been associated with a high proportion of carbonate. From this it has been inferred that sodium carbonate, or "black alkali," is the chief cause of the impermeability of the soil.

Other investigators who have identified the basic constituents of the soil solution as well as the acids have found that when these bases consist chiefly of calcium and magnesium the soil does not show much

change in its physical character when the solution is diluted. On the other hand, when the dissolved bases are chiefly sodium and potassium the dilution of the soil solution is accompanied by a pronounced reaction of the soil that is manifested in several ways, among which impermeability to the movement of water is one of the most striking.

Before undertaking a detailed discussion of the reactions that take place and the changes that occur in the physical condition of the soil when the soil solution is diluted, it may be proper to cite some examples of changes in the balance of the constituents of the solution that go on during the process of dilution. There are at least three ways in which such dilutions may be made in the laboratory: (1) By digesting similar samples of soil with different quantities of water; (2) by repeated digestions of the same sample, withdrawing a part of the solution after each digestion and replacing it with an equal quantity of distilled water; (3) by leaching a sample of soil with distilled water, analyzing successive fractions of the percolate. While none of these methods exactly simulates conditions that exist in the field, each of them gives results that contribute to an understanding of the reactions that may be brought about by the application of irrigation water to a tract of salty land.

Reference has been made in a preceding chapter to the fact that when samples of the same soil are digested with different quantities of water and a portion of the water subsequently withdrawn for analysis it is found that with some soils the apparent salt content is higher when a large quantity of water is used for digestion than when a smaller quantity is used. This phenomenon might be interpreted as indicating that some of the soluble material of the soil is very slightly soluble and that as more water is used for digestion more and more of this slightly soluble material comes into solution.

This interpretation is not wholly satisfactory, because it can be shown that if the solution obtained by digesting a soil sample with a large volume of water is concentrated by evaporation, precipitation does not occur until the solution has become much more concentrated than the solutions obtained by using a smaller quantity of water for digestion. Furthermore, the known solubility under laboratory conditions of such salts as would be indicated from the constituents identified in the solution is much higher than is obtained from these digestion experiments. The implication is that some part of the soil, presumably the clay, reacts toward some of the soluble constituents in much the same way as water does. The result of this reaction appears to be to retard the passing of these constituents into the soil solution.

A more detailed discussion of these relationships between the soil and its solution may be postponed for the present until more of the pertinent facts have been established. Some of these facts may be brought out by comparing the character of the solutions obtained by various dilutions. It can be shown that the increased dilution of the soil solution with certain types of soil not only increases the apparent salt content of the soil but modifies the character of the solution in so far as this is indicated by the relative proportions of its constituents.

An example of these differences in the quantity and character of the material dissolved from a soil by different quantities of water is shown in Table XVIII. The soil used in this experiment was from an irrigated field in Arizona. The solution of this soil showed only traces of calcium

and magnesium. The soil was of such texture that it was supersaturated with 30 per cent of water. This made it possible to extract with a suction filter enough of the solution for analysis when 100 parts of soil was digested with 40 parts of water. The experiment included digestion of equal quantities of the same sample of soil with quantities of water ranging from 40 parts per 100 up to 2,500 parts per 100. After the soil had been digested with water for 24 hours, with repeated shaking, a portion of the solution was withdrawn from analysis.[10] The total solids were determined by evaporation and the organic matter by igniting the dried residue. The other constituents identified were the carbonate, bicarbonate, chlorin, and sulphate.

TABLE XVIII.—*Effect of diluting the soil solution on the balance of its constituents, the total solids being expressed as percentages of the dry weight of the soil and the constituents as percentages of the total solids* [a]

Dilution ratio of water to soil.	Total solids.	Constituents as percentage of total solids.				
		Organic matter.	$CO_3+\frac{HCO_3}{2}$	Cl.	SO_4.	Total acids.
0.4:1	0.76	7.3	9.7	19.3	35.7	64.7
0.5:1	.77	7.8	9.7	17.1	34.6	61.4
1.0:1	.82	9.7	11.6	14.1	32.7	58.4
2.5:1	.87	10.5	12.9	14.0	29.7	56.6
5:1	.94	9.9	14.4	14.2	27.5	58.1
10:1	.99	12.1	16.3	14.1	25.8	56.2
25:1	1.12	15.2	20.1	12.5	20.8	53.4

[a] Reported by J. F. Breazeale.

The analysis of these solutions showed that the total quantity of dissolved material obtained from a unit quantity of soil increased from 0.76 per cent when 40 per cent of water was used to 1.12 per cent when the 2,500 per cent of water was used. The important constituents of the solution are reported in four groups—organic matter, carbonates, chlorin, and sulphate. When these constituents are reported as percentages of the total solids it is observed that two of them, the organic matter and the carbonates, show increasing percentages with increasing dilutions, while the other two show decreasing percentages. If these constituents were reported as percentages of the original soil it would be seen that while the percentages of chlorin and sulphate are practically the same for all dilutions, the percentage of organic matter increases from 0.055 per cent with 40 per cent of water to 0.170 per cent with 2,500 per cent of water. The increase in the percentage of carbonate and bicarbonate to the dry soil is even more marked, being from 0.074 with 40 per cent to 0.225 at 2,500 per cent.

It is obvious from the results of this experiment why investigators hesitate to make assumptions concerning the concentration or character of the soil solution as it is available to crop plants when their only information is based upon the analysis of extracts made with 5, 10, or even 20 parts of water to 1 part of soil. With such a soil as that used in the

[10] This experiment was conducted and the analysis made by J. F. Breazeale.

experiment just described, 10 per cent of water would be enough to support plant growth. With this quantity of solution in the soil it is not unreasonable to assume that the actual quantity of dissolved material per unit of soil would be even less than is shown with 40 per cent of water, and this solution would contain a smaller proportion of both organic matter and carbonate.

From other observations that have been made on solutions extracted from irrigated soils it seems probable that under ordinary field conditions the soil solution will only rarely show a reaction for normal carbonate, that is to say, will give a pink color with phenolphthalein. On the other hand, it is almost equally uncommon to find a saline soil containing appreciable quantities of sodium salts that does not show such a reaction when it has been leached with pure water.

In the experiment just described the original sample of soil was subdivided and each part was digested once with a certain quantity of water. This method of treatment is one that is used in making analysis of soils, but it does not correspond to anything that ordinarily goes on in the field. The second method of treatment referred to at the beginning of this chapter bears some resemblance to the process of reclaiming a saline soil by repeated copious irrigations.

According to this second method of treatment, a large sample of soil, 3 kgm., was saturated with water, 900 cc., and the mixture was kept in a closed jar for 24 hours with repeated shaking. After 24 hours a part of the solution, 120 cc., was withdrawn by means of a suction filter, and an equal quantity of distilled water was again added to the soil. In this way a portion of the dissolved material was removed with each sample of the solution, and with each withdrawal and replacement the solution became more dilute.

The soil used in the present experiment was of the same type as that used in the previous experiment, though it showed somewhat less soluble material. The extracted solutions again showed only traces of calcium and magnesium, so that these elements were not determined quantitatively. The analytical methods used were the same as those used in the previous experiments.[11] The analytical results of this dilution experiment are shown in Table XIX. The total solids are given as percentages of the original soil and the constituents as percentages of the total solids.

The successive withdrawals of the solution resulted in the gradual reduction of its concentration. This reduction in concentration was accompanied by a change in the proportions of the constituents, as shown in the table, and also by a change in the physical character of the wet soil. It was observed that while the first withdrawals were made without difficulty the later ones were harder to get out, so that after the fourteenth extract the experiment had to be discontinued because the solution could no longer be obtained.

In this experiment, as in the preceding one, it was found that as the soil solution became more dilute the proportion of dissolved oragnic matter and of carbonate increased while the proportion of the chlorin and the sulphate decreased. The character of the solution at the end of the experiment was very different from that at the beginning. This difference in the character of the solution was also reflected in a change in the physical character of the soil.

[11] This experiment was conducted by J. F. Breazeale, who also made the analyses.

The conditions that obtain in the field where a saline soil is being reclaimed by leaching may be approximated most closely in the laboratory by using a glass pot, such as is shown in figure 4, or a glass tube partially filled with soil to which distilled water is added at the top. The water percolates downward through the soil, dissolving the soluble material, and is replaced by subsequent additions of water. The soil solution thus replaced escapes below where it may be collected for analysis.

TABLE XIX.—*Effect of diluting the soil solution on the balance of its constituents, the total solids being expressed as percentage of the dry weight of the soil and the constituents as percentages of the total solids* [a]

Extract No.	Total solids.	Constituents as percentage of total solids.				
		Organic matter.	$\frac{CO_3+HCO_3}{2}$	Cl.	SO_4.	Total acids.
1	0.493	6.9	9.4	19.2	29.3	57.9
2	.480	7.0	8.8	16.4	32.6	57.8
3	.420	8.1	9.1	15.4	31.2	55.7
4	.356	7.6	10.3	15.7	31.8	57.8
5	.312	8.0	10.0	15.2	31.9	56.1
6	.274	8.9	10.7	14.7	31.4	56.8
7	.228	10.2	11.5	15.4	29.4	56.3
8	.216	10.2	12.0	14.2	29.8	56.0
9	.179	10.6	14.0	14.2	28.4	56.6
10	.178	11.6	14.5	13.8	26.7	55.0
11	.141	17.1	14.9	13.1	27.0	55.0
12	.136	14.5	16.0	11.1	24.9	52.0
13	.119	16.8	17.0	12.5	22.7	52.2
14	.108	16.4	16.0	12.2	19.5	47.7

[a] Reported by J. F. Breazeale.

This method of leaching soils is subject to the same difficulties in the laboratory as are met in the field. With certain soils the dilution of the soil solution is accompanied by a change in the physical character of the soil such that the rate of percolation is reduced to the vanishing point. With soils that show this reaction to a marked degree it is no more practicable to conduct leaching experiments in the laboratory than it is to reclaim them in the field.

It has been observed by a number of investigators that when the soil solution contains a fairly high proportion of calcium and magnesium it is possible to dilute the solution without causing the soil to become impermeable. On the other hand, when the soil solution contains a very low proportion of calcium and magnesium and a high proportion of sodium and potassium the dilution of the soil solution is likely to result in making the soil nearly or quite impermeable to water.

It has been shown that this condition of potential impermeability may be induced in a soil that is naturally permeable by the application of even small quantities of sodium salts. Cummins and Kelley (*6*) cite a case where the application of sodium nitrate as a fertilizer to the soil of the Citrus Experiment Station at Riverside, Calif., has resulted in making the soil become relatively impermeable to water.

It should be definitely understood that there is a real distinction implied by the term potential impermeability as applied to irrigated soils. The same soil may be actually permeable and potentially impermeable. A soil rarely shows symptoms of impermeablity while the soil solution contains a large proportion of dissolved material. The existence in the solution of appreciable quantities of such strong electrolytes as chlorin, sulphate, or nitrate appears to inhibit the soil reaction that makes for impermeability to water. This is true whether the solution is rich or poor in calcium and magnesium. Thus an impermeable soil may be made temporarily permeable by treating it with sodium chlorid or sodium sulphate or by leaching it with a solution of these salts. On the other hand, such treatment would almost certainly make a soil potentially impermeable in that a subsequent dilution of the soil solution, as by leaching the treated soil with distilled water, would induce impermeability.

In view of what has just been said it will be clear that experiments in the dilution of the soil solution by leaching, either in the laboratory or in the field, may be expected to be successful only when the solution contains a substantial proportion of calcium and magnesium. Unless this is the case the experiment is doomed to end in disappointment. Even when this condition is fulfilled it is often found that the rate declines as the leaching goes on. But the decline is not likely to continue unless in the readjustments that take place the preponderance of sodium becomes large.

In the leaching experiments now to be described it will be observed that both the soils used showed large proportions of soluble calcium and magnesium. With one of the soils these proportions continued high to the end of the experiment. With the other it declined as the experiments proceeded.

The soil used for the first of these two leaching experiments was taken from an irrigated field in Arizona. When thoroughly dry it was pulverized and placed in a glass tube of such a diameter that 1,000 gm. of the dry soil occupied about 16 inches of the tube. The bottom of the tube was stoppered with a perforated cork. The column of soil was then leached with distilled water and the percolate was collected in successive fractions of 50 cc. each.

These successive percolates were then analyzed with results as shown in Table XX.[12] The total solids are reported as percentages of the percolate, and the constituents that were identified are reported as percentages of the total solids. As the leaching progressed the solutions obtained became progressively more dilute and the character of the solution was also changed. At first the chief constituents were calcium,[13] chlorin, and nitrate. After the fifth percolate, when 250 cc. of water had passed through the soil, the nitrate practically disappeared. The sulphate content of the first leachings was very low. As the solution became more dilute the actual quantity of sulphate increased somewhat, while the proportion of sulphate to the total salts increased very greatly.[14]

[12] This experiment and the analyses were made by J. F. Breazeale.

[13] The ratio of calcium to magnesium continued throughout the experiment to be approximately as 8 to 1.

[14] Breazeale has observed in another experiment that while calcium sulphate is soluble in distilled water to the extent of approximately 2,000 parts per million, its solubility is reduced in the presence of calcium chlorid. With 26 per cent calcium chlorid he found less than 500 parts per million of dissolved calcium sulphate, while with a saturated solution of calcium chlorid he found calcium sulphate practically insoluble.

TABLE XX.—*Effect of diluting the soil solution by leaching when the solution is rich in calcium and magnesium; 1,000 gm. of soil, 50 cc. fractions of percolate*

Percolate No.	Total solids.[a]	Percentage of constituents to total solids.					
		Ca + Mg.	$\frac{HCO_3}{2}$	Cl.	SO_4.	NO_3.	Total acids.
1	37.58	27.1	2.0	35.5	0.2	5.0	42.7
2	26.52	35.2	2.3	40.9	.3	5.1	47.6
3	21.57	36.2	2.6	41.2	.4	4.9	49.1
4	10.95	37.5	4.4	44.7	.9	6.3	56.3
5	4.45	28.7	3.0	42.5	4.2	5.9	55.6
6	2.82	25.5	1.5	47.2	4.9	2.1	51.8
7	2.86	22.4	.8	44.1	4.0	1.4	50.3
8	2.04	21.5	1.3	43.0	5.9	Tr.	50.2
9	1.34	24.6	2.0	38.0	10.2	0	50.2
10	.83	22.8	3.6	30.2	19.8	0	53.6
11	.57	19.4	3.2	23.3	30.3	0	56.8
12	.41	21.2	6.6	7.5	43.2	0	57.3
13	.32	21.6	7.5	5.3	46.8	0	59.6
14	.21	24.5	11.5	5.3	45.7	0	62.5
15	.18	20.7	9.1	2.2	40.3	0	51.6

[a] In percentage of solution, including organic matter.

The proportion of chlorin remained fairly constant until the tenth percolate when it began to decline rapidly. At this time the concentration of the solution had been reduced from 37 per cent to 1 per cent. When the proportion of chlorin began to decline rapidly the proportion of carbonate and sulphate began to increase correspondingly. This sequence of changes in the character of the solution obtained from the same sample of soil as a result of leaching illustrates what may go on in a field that is being reclaimed by the same process. The leaching results not only in reducing the concentration of the soil solution but also in changing its character. This change in the character of the soil solution appears to be associated with what may be termed the relative motility of the various constituents of the solution. Certain of these, such as the nitrate and the chlorin, move through the soil very readily, while the sulphate and the carbonate are more sluggish.

In the leaching experiment just described the soil solution was at first highly concentrated, and this concentration declined very rapidly with each successive fraction of the percolate. The conditions of that experiment differed from conditions that ordinarily exist in the field in that when the leaching began the soil in the tube was entirely dry. In an irrigated field the moisture content of the surface inch or two may be low, but below that one finds moist soil. The application of water to the top of a column of dry soil brings into solution at once a large part of the soluble material contained in the upper part of the column. As the resulting solution moves downward it continues to take up more soluble material until it reaches the bottom of the column and emerges as percolate. Each successive fraction of the descending column of water would come in contact with soil from which a large part of the soluble material had been removed, and the concentration of each succeeding fraction would be correspondingly reduced.

The conditions of this leaching experiment also differed from conditions in the field in that the soil in the tube had been thoroughly mixed when

placed in the tube and the soluble material was presumably distributed evenly throughout the mass. In the field where water is lost by evaporation from the surface layer of soil there is usually found an accumulation of soluble material at or near the surface. When water is applied this passes into solution and moves downward with the water.

In order to approximate these field conditions somewhat more closely another experiment was set up. The soil used was a permeable sandy loam from the Newlands reclamation project in Nevada. The leaching was done in glass pots, like the one shown in figure 4. Four pots were used, each containing 200 gm. of soil. The soil was first moistened thoroughly and allowed to stand for some time to establish conditions of equilibrium between the solution and the soil. Each pot was then treated with 1 gm. of sodium chlorid which was mixed into the moist surface soil so that it might go into solution. The soil was then leached by adding 10 cc. of distilled water to each pot. The percolate from each leaching was collected below and analyzed, with the results shown in Table XXI.

TABLE XXI.—*Effect on the balance of the constituents of diluting the soil solution by leaching, the total salt being expressed as percentage of the solution and the constituents as percentage of reacting values based on the total acids*

Leaching No.	Total salts.[a]	Percentage of reacting values.			
		r Ca.	r HCO_3.	r Cl.	r SO_4
1	0.295	33.4	6.8	2.3	91.0
2	1.525	34.6	1.7	80.3	18.0
3	1.600	33.2	.8	80.0	19.2
4	2.160	30.4	.6	86.7	12.7
5	1.840	29.4	.7	87.3	12.0
6	1.575	29.4	.8	86.7	12.5
7	1.440	29.7	1.0	85.2	13.8
8	1.185	24.5	1.2	83.1	15.7
9	.905	21.6	1.5	80.0	18.5
10	.725	13.3	3.6	75.2	21.2
11	.600	15.5	3.1	72.6	24.3
12	.480	12.4	5.5	69.0	25.5
13	.340	10.1	11.3	67.5	21.2
14	.265	8.5	11.8	64.6	23.6
15	.230	11.5	20.5	60.2	19.3
16	.195	8.9	23.2	60.2	16.6
17	.150	8.7	33.4	54.2	12.4
18	.127	7.3	34.2	56.2	9.6

[a] Determined by electrical resistance.

While the ratio of water to soil for each fraction of the percolate was the same in this experiment as in the preceding one, the rate of leaching was different in that each successive application of water was made only after percolation from the previous application had ceased. Often the pots stood overnight between leachings, so that diffusion tended to equalize the distribution of the solution constituents and retard the rate of displacement. These conditions resulted in a much slower rate of decline in the concentration of the successive percolates than that shown in the preceding experiment.

The addition of the sodium chlorid to the solution at the beginning of the experiment also caused some significant changes in the solution.

It would be natural to expect that succeeding percolates would show a large increase in the proportion of chlorin and consequent decreases in the proportion of carbonate and sulphate. The actual quantities of carbonate and sulphate in the solution were not at first materially changed. This was not true with the calcium.[15] While the first percolate after the addition of the sodium chlorid showed no pronounced change in the proportion of calcium to the total salts, the actual quantity of calcium in the solution increased from less than 300 parts per million to more than 1,600 parts per million. This reaction by which sodium added to the soil solution tends to replace combined calcium will be discussed later.

As these leachings continued the concentration of the percolates became gradually reduced, the proportion of calcium declined rapidly, the proportion of the chlorin declined also, but less rapidly, while the proportion of carbonate began to increase as the solution became more dilute. Not only did the proportion of carbonate (identified in the solution as bicarbonate) increase as the percolates became more dilute but the actual quantity increased also. The first percolates showed 120 parts per million of HCO_3, while the final one showed 450 parts per million.

These various experiments in diluting the soil solution all show that such dilution, by whatever method it is accomplished, does not operate in the same way with the different constituents of the solution. The evidence available appears to justify the inference that there are continuing reactions between the soil and its water, so that the character of the solution is essentially modified as its concentration changes. These reactions between the soil and its water appear to operate not only to influence the character of the solution but also to influence the physical character of the soil in its relation to the movement of water through it. It is well known also that these changes in the physical character of the soil are manifested when the soil is dried. The same physical condition that retards the movement of water through the soil causes the soil particles to become cemented together into a solid mass when the water is lost by drying. Soils that are readily permeable to water usually crumble on drying.

EXCHANGE REACTIONS IN THE SOIL SOLUTION

The leaching of a saline soil in the field must be done ordinarily with irrigation water. Such water always contains some dissolved material derived from its contact with the soil. When it is obtained from wells or from most streams the water is itself a soil solution. The character of this solution is a matter of large importance. Its use on the land may result in a complex of conditions wholly different from the one already existing. In this respect again leaching experiments in the field are likely to differ from those conducted in the laboratory.

It has been noted above that certain changes in composition of the soil solution take place when the concentration is changed, as by the addition of pure water. When another solution is added to the one already present in the soil, the reactions that follow involve not only the two solutions but the soil also takes part in them. Certain constituents in the blended solutions may be taken up by the soil and other constituents be released from combination with the soil and pass into solution.

[15] In these solutions the proportion of magnesium was so low as to be negligible.

In the second of the two leaching experiments described on the preceding pages it was shown that the addition of sodium chlorid to the soil solution was followed by a pronounced increase in the quantity of calcium in the solution. This phenomenon, which has been called the exchange of bases, is one that has been reported upon by several investigators.[18]

The exact nature of this phenomenon has not been determined. It has been observed that exchanges take place between the basic constituents of the soil solution and the basic constituents of certain insoluble or very slightly soluble substances in the soil. These exchanges of basic constituents that take place between the solution and the soil are probably more important in their effect on the physical properties of the soil than are those changes in the proportion of the acid constituents that have been discussed above. Until the nature of these reactions is better understood it is not possible to do more than speculate concerning their processes or their exact character. The results may be recognized without difficulty.

When a soil is treated with a solution of a sodium or potassium salt that is more concentrated with respect to these elements than the solution already present, a part of the basic element is withdrawn from the solution and its molecular equivalent of other bases passes into solution from combination with the soil, until a new condition of equilibrium is established. Similar reactions take place when other basic elements are used, such as calcium, magnesium, iron, and aluminum. The consequences of these exchange reactions is to modify the character of the soil as well as of the solution.

These exchange reactions proceed in the direction of establishing a condition of equilibrium between the soil and its solution. It has been found that a limit may be reached beyond which no further reaction takes place. With the soil as with the solution when the limit of saturation is reached reaction ceases. A soil is said to be saturated with respect to a certain basic element when it ceases to show an exchange reaction except when the concentration of that element in the solution is increased.

The results of these exchange reactions on the physical properties of the soil are strikingly different with the different bases. With respect to their effect on the soil the bases that occur most commonly in the soil solution fall into two groups. These groups are sometimes designated as the alkaline and the earthy bases. The alkaline group includes sodium, potassium, and ammonia. The earthy group includes calcium, magnesium, iron, and aluminum. While it may be possible to distinguish between the reaction effects produced in the physical condition of the soil by elements of the same group, these differences if they exist are very slight as compared with the differences produced by representative elements of each. In order to simplify the discussion of the effects produced by the elements of each group on the physical condition of the soil, one element from each may be taken as typical. Thus the alkaline group may be represented by sodium and the earthy group by calcium.

Before proceeding to discuss in detail the effects on the physical properties of the soil of the exchange reactions between sodium and calcium it may be well to establish more definitely the fact that such exchange reactions actually take place. Evidence on this point has been contributed by a number of investigators, but its interpretation has been

[18] See: WAY, J. THOMAS (*31*, *32*), and GEDROIZ, K. K. (*9*). A comprehensive bibliography of this subject is given by Cummins and Kelley (*6*).

confused by many authors who have held the view that the soil absorbs substances from solution and who have not been clear that such absorption constituted but one part of an exchange reaction. The results of experiments which show quantitatively the extent of such exchange reactions are not numerous, probably because many investigators do not make quantitative determinations of sodium in the course of their experiments. The early experiments of Way (*21, p. 332,334*) showed that when a soil which contained only traces of water-soluble calcium was leached with solutions of potassium and sodium salts the percolate was practically free from potassium or sodium but instead contained calcium in abundance together with the acid radical contained in the original leaching solution.

More recently Gedroiz (*8*) has shown that a soil which would give up to 20 consecutive digestions with water (ratio of 5 : 1) only 0.176 per cent of CaO gave from similar treatment with a normal solution of sodium chlorid 1.244 per cent CaO. In a later paper the same author (*9*) describes an experiment in which a sample of soil was first digested repeatedly with solutions of sodium chlorid until equilibrium was established between the solution and the soil. The soil was then washed, dialyzed, and dried. The treated soil was then analyzed by digestion with 10 per cent hydrochloric acid and its calcium content compared with that of the original untreated sample. The original sample contained 1.36 per cent CaO extractable by 10 per cent hydrochloric acid, while the sample that had been brought into equilibrium with a normal solution of sodium contained only 0.36 per cent CaO extractable in the same way. This result indicates that the absorption by the soil of a certain quantity of sodium from the solution of sodium chlorid had resulted in releasing into solution 1 gm. of CaO or 0.715 gm. calcium from 100 gm. of soil.

The quantity of sodium that was absorbed by the soil during the treatment described was also determined by analyzing samples before and after treatment. These analyses showed that the original soil contained 0.05 per cent Na_2O, while after treatment with the sodium-chlorid solution it contained 1.42 per cent. This is equivalent to 1.016 gm. of sodium absorbed by 100 gm. of soil.

The absorption of this quantity of sodium was accompanied by the release of other bases than calcium from combination with the soil. Two of these, magnesium and potassium, were identified by the analyses. It was found that the absorption of sodium had caused the release of 0.12 per cent of MgO and of 0.03 per cent of K_2O. The analytical results of this experiment are summarized in Table XXII.

TABLE XXII.—*Percentages of combined (not water soluble) bases in a sample of Russian black earth in its original condition and after being brought into equilibrium with a normal solution of sodium chlorid* [a]

Sample.	Constituents soluble in 10 per cent hydrochloric acid, in percentage of dry soil.			
	CaO.	MgO.	K_2O.	Na_2O.
Original soil	1.36	0.87	0.52	0.05
Treated soil	.36	.75	.49	1.42
Replaced	1.00	.12	.03	.....
Absorbed	.....	.....	.....	1.37

[a] From Gedroiz.

The soil used by Gedroiz in this experiment was rich in combined calcium and poor in sodium. When treated with a solution of sodium chlorid its chemical composition with respect to these bases was profoundly changed. It was observed also that its physical character was changed, but its characteristics with respect to permeability before and after treatment were not reported upon.

Being already rich in calcium it would not be expected that the black earth with which Gedroiz worked would absorb much more calcium and thereby release other bases. The quantity of combined sodium which it contained was so small that there was very little of it to be replaced.

In another experiment reported by the same author a sample of the same black earth was treated with a normal solution of calcium chlorid in the same way as described above for the treatment with sodium chlorid. The sodium was not determined in the second experiment, but the quantities of calcium, magnesium, and potassium extracted from the soil by 10 per cent hydrochloric acid are reported in Table XXIII.

TABLE XXIII.—*Percentages of combined (not water soluble) bases in a sample of Russian black earth in its original condition and after being brought into equilibrium with a normal solution of calcium chlorid* [a]

Sample.	Constituents soluble in 10 per cent hydrochloric acid in percentage of dry soil.		
	CaO.	MgO.	K_2O.
Original soil	1.36	0.87	0.52
Treated soil	1.51	.76	.49
Absorbed	.15	.....	.....
Replaced	.....	.11	.03

[a] From Gedroiz.

The results of these experiments show quantitatively the exchange reactions that may take place between the bases combined in the soil and those in solution in contact with the soil.

The fact that such exchanges take place has been observed by several other investigators. It is obvious that such reactions take place in an irrigated field, as will be made apparent by comparing the composition of the irrigation water applied to a field and the drainage water discharged from it.

THE COMBINED BASES AND PERMEABILITY

In discussing the reactions of the basic elements that exist in the soil solution it is convenient to recognize two groups—the alkaline, which includes sodium, potassium, and ammonia, and the earthy, which includes calcium, magnesium, iron, and aluminum. The elements of both groups may take part in exchange reactions between the solution and the soil. The effect of such reactions on the side of the soil is to produce one set of physical conditions when the combination is with the alkaline bases and a very different set of conditions when these are replaced by the earthy bases.

These differences in the physical condition of the soil are manifested conspicuously in at least three ways—in permeability to water, in

turbidity of the water extract, and in cementation on drying. When the preponderance of combined bases is with the alkaline group the soil is less permeable to water, the soil extract is more turbid, and the soil tends to cement together on drying. When the preponderance is with the elements of the earthy group these symptoms are manifested in the opposite direction.

It should be kept in mind that the full development of these symptoms in the direction of the alkaline response does not take place while the soil solution contains large quantities of the stronger acid electrolytes, such as chlorin, sulphate, or nitrate. In other words, the presence of these acid electrolytes in the solution tends to prevent the manifestation of the physical effects that follow the replacement of the earthy bases by the alkaline bases in the soil combination. The removal of these dissolved acid ions by leaching the soil or the dilution of the soil solution permits the physical effect of the combination of the alkaline bases with the soil to be shown.

The replacement by an alkaline base of the earthy bases combined with the soil and the effect of this exchange on the permeability of the soil may be observed by following the course of events in a simple leaching experiment. In such an experiment a soil of good permeability should be used. It should be treated with sodium chlorid or sodium sulphate or leached for a time with a solution of one of these. It should then be leached with distilled water to remove the acid electrolyte from the soil solution. An examination of the percolates obtained from the leachings with the salt solution will show that these differ from the solution applied to the soil in that they contain less sodium and that this decrease in sodium is made up by other bases, chiefly calcium. After the leachings with distilled water are begun the percolates become more dilute and the percolation rate becomes much slower and may cease altogether.

The same physical condition of the soil that makes for impermeability to water is also shown by increased turbidity of the water extract of the soil. This may be demonstrated by taking a small quantity of soil used in the leaching experiment just described and shaking it up with water. The use of 10 parts of water to 1 part of soil gives a good example. Another sample of soil taken after the leaching experiment is completed and treated with water in the same way shows the contrast in the turbidity of the extract. These differences in turbidity of the water extract of a sample of salty soil before and after leaching are shown in figure 6. Each of the tubes shown in the figure contained 5 gm. of soil and 50 cc. of water. After the mixture was thoroughly shaken, the tubes stood for two days before the photograph was made. In the tube at the right which contained the unleached soil the solution cleared within a few minutes. In the other tube only the larger particles settled out, the fine material remaining suspended in the solution.

The differences in the cementation properties of a soil in which the earthy bases have been replaced by an alkaline base may be shown by drying a sample from the leaching experiment described above and comparing it with a sample of the original soil that has been saturated but not leached. Such comparison shows that the alkaline treated soil becomes harder on drying than the original permeable soil.

LEACHING SALINE SOILS IN THE FIELD

In the ordinary practice of irrigation the aim is to apply the water uniformly to the surface of the land. To this end various methods of distribution are resorted to, such as furrows, checks, borders, basins, and contour ditches. In preparing the land for irrigation a good deal of labor is devoted to leveling the surface, so that a uniform distribution of the water may be accomplished. The implication is that if the water is applied uniformly to the surface it will soak into the ground with equal uniformity in each check or along each furrow. As a matter of fact, this does not happen. The soil as it occurs in the field is anything but uniform in texture and in permeability. These differences are often very great at points only a few feet apart. When this is so it is not to be expected that water applied uniformly to the surface of the land will penetrate the soil to the same depth in all parts of the field.

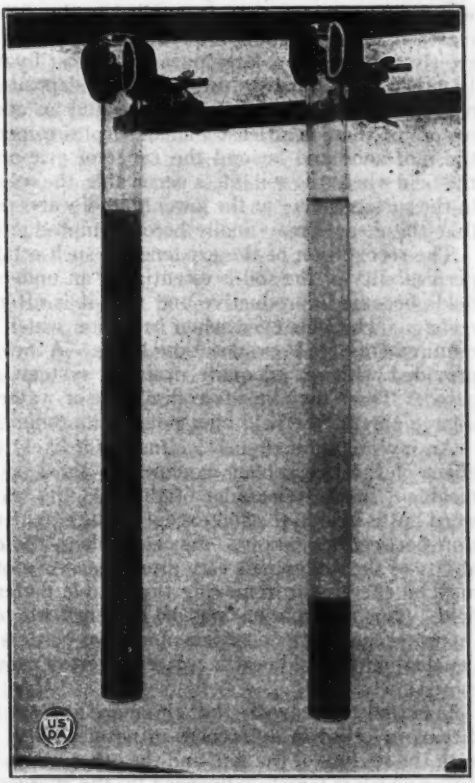

FIG. 6.—Turbidity of solution from the same soil (No. 369) before and after leaching. In each case the tube contains 5 gm. of soil in 50 cc. of water. The tube at the right contains untreated soil which carried 2 per cent of salt. The tube at the left contains a sample of the same soil after leaching. The removal of the salt by leaching has caused a marked and persistent turbidity.

An example of the differences that may be encountered in the penetration of water applied to a well-leveled check is shown in Table IV and illustrated in figure 2. This example is taken from the Newlands Experiment Farm in Nevada. The observations were made at two points in the same check only 15 feet apart. At one of these points the water did not penetrate beyond the first foot, while at the other it reached the third foot and may have passedon into the fourth. Similar instances of differences of penetration may be observed in any irrigated field.

Such differences in the character and permeability of the soil constitute one of the most serious problems in irrigation, both as regards the watering of crops and the prevention or remedy of the accumulation in the soil of injurious quantities of soluble material.

If it were possible to bring about a uniform penetration of irrigation water in the field there would be no such thing as the accumulation of

those soluble substances that cause what is known as the alkali problem. Were it possible to obtain even approximately uniform penetration of water the soluble material would be carried downward with each successive irrigation, and the subsoil accumulations could be removed by artificial drainage where the natural drainage conditions were inadequate.

With conditions as they are, such that the water penetrates readily in some parts of the field or check and very slowly and only to a short distance in other parts, there is a tendency for initial diversities to be exaggerated with the passage of time and with repeated applications of water. The water that is applied to the field carries some dissolved material, often substantial quantities. Some of this water is used by the growing crops, but a large part of it is lost by evaporation from the soil. In either event the dissolved material is deposited in the soil. Where the conditions of permeability are good and an adequate quantity of water is applied there is at least a small surplus to percolate downward beyond the root zone and beyond the range of evaporation. In those spots in the field where the soil is less permeable, the soluble material accumulates in the surface soil or at the lower limit of water penetration, with the result that these spots may finally become unproductive.

The recognition of the existence of such conditions of diversity in the permeability of the soil is essential to an understanding of how irrigated fields become unproductive and why it is often found to be difficult to reclaim such fields even when irrigation water is used in excess of crop requirements and evaporation losses. A field of saline soil may be provided with an adequate drainage system and may be heavily irrigated. There may be a free discharge of water from the drains and yet a large part of the field may remain unproductive. (See Pl. 2, B.)

An investigation of such a situation is likely to show that the leaching effect of the irrigation is confined to those spots where the soil is permeable. In the remainder of the field the water is not moving downward but is held in the soil except to the extent that it is lost by evaporation between irrigations. In fields where the differences in the permeability of the soil are not very pronounced, a protracted period of leaching may be effective in removing the soluble material from all parts of the field. This reclamation may be hastened wherever it is possible to hold the water in place by a system of interior borders that will tend to equalize penetration by holding the water longer on those spots where it soaks in more slowly.

It is well to recognize that there are at least two different sets of conditions involved in differences in permeability. One of these has to do with the texture of the soil, and the other has to do with its physical condition which is largely influenced by the character of its combined bases; that is to say, a soil that is made up largely of clay and fine silt is less permeable than a soil composed largely of sand, providing both types are in the same condition as regards their combined bases. When a check or border includes both types of soil it is well worth while to subdivide it by interior borders which conform to these differences of soil type. Such subdivision makes for economy in the use of water whether for leaching the soil or for irrigating crops.

Where the differences in permeability within a border are due chiefly to the physical condition of the soil resulting from the character of the combined bases it is possible to obtain more uniform penetration of the water by making local applications of salts that will improve the

physical conditions through the exchange reactions described above. For this purpose such salts as calcium sulphate (gypsum) or aluminum sulphate are among the most available. Of these two salts gypsum is the cheaper and more generally accessible. It has the disadvantage of being less soluble than aluminum sulphate and consequently of reacting more slowly.

The beneficial effects that follow the use of gypsum on soils that do not take water readily have long been known, and this salt is extensively used on irrigated land. The assumption that the physical condition of the soil that is associated with slow permeability was due to the existence of sodium carbonate in the soil solution made it natural for earlier investigators to explain the effect of gypsum as a reaction with sodium carbonate. When solutions of sodium carbonate and of calcium sulphate are brought together a reaction takes place by which calcium carbonate is precipitated from the solution. It was assumed that a similar reaction takes place when calcium sulphate is applied to a soil. It is not essential in the present connection to decide whether the calcium applied as gypsum reacts with substances in the soil solution or takes part in exchange reactions with the soil. The obvious fact is that the application of gypsum to a soil that is slowly permeable to water generally results in its improvement.

It has been noted above that gypsum is not very soluble and that its effectiveness is limited on that account. It requires about 500 parts of water to dissolve 1 part of gypsum under favorable conditions. In many situations this low solubility is not a serious disadvantage because the reactions in the soil may go on slowly and be long continued. Where the conditions appear to require more effective action than may be obtained from gypsum it is possible to use calcium in a more soluble form as calcium chlorid or calcium nitrate or to use aluminum sulphate. This latter salt which occurs in nature in limited quantities is also manufactured for use in industry and for clearing turbid waters for domestic and industrial use. It has been found that aluminum, like calcium, reacts through the soil solution with the soil to modify its physical condition (*9*, *15*).

In the application of these salts to the soil in the field it would seem advisable to limit their use to those spots where the soil is impermeable rather than to apply them to the whole field. The end sought for is to obtain more uniform conditions of water penetration, and this end may be attained more economically by confining the treatment to the spots that show the need of it. After a field has been irrigated an exploration of it, using a sharp pointed steel rod or a soil augur, makes it possible to locate the spots where the water has not penetrated to the depth desired. These spots may then be given appropriate treatment.

An example of the effect of an application of aluminum sulphate to increase the permeability of the soil is shown in Plate 1. The field in which this experiment was made is at Sacaton, Ariz. A number of borders in this field included spots on which there was no crop growth, though other places in the same borders produced good crops. In the experiment illustrated in the figure two small basins were made side by side in one of the bare spots. To one of these, the one shown on the right, aluminum sulphate was applied at the rate of 5 tons per acre; the other basin was left untreated. The two basins were then irrigated with equal quantities of water about 3 inches in depth. The water

was absorbed in the treated basin within about five hours. The photograph shown in the figure was taken 54 hours after the water was put on. It shows that the water was still standing in the untreated basin while the soil in the treated basin was beginning to dry and crack.

There is another condition of impermeability sometimes encountered in irrigated land that differs from those described above in that it occurs in a zone of limited thickness somewhat below the surface of the soil. This condition, which has been referred to as "hardpan" or "plowsole," is sometimes found in soils that have not been irrigated, and it also develops under certain conditions in irrigated lands (*10*).

The formation of hardpan appears to be due to the precipitation of substances from the soil solution at the point below the soil surface where evaporation takes place. Such precipitation may be due in part to evaporation and in part to the loss of carbon dioxid from the soil solution. The formation of indurated layers in the soil, sometimes referred to as "caliche," is probably due largely to the escape of carbon dioxid and the consequent precipitation of calcium carbonate. These subsurface impermeable layers often interfere seriously with the penetration of water. When they are not too thick and hard, they are often broken up by deep cultivations; otherwise blasting may be resorted to if conditions justify that expense.

The existence of an underground water table in effect constitutes a barrier to the downward percolation of water through the soil unless the drainage conditions are such that the whole body of underground water is free to move. Furthermore, when the underground water stands close to the surface of the ground, it suffers losses by evaporation, and consequently deposits its dissolved material at the point where it evaporates. This deposition of dissolved material from underground water is one of the most prolific sources of trouble in irrigated land.

The movement of water through saturated soil is usually very slow. Consequently, readjustments of underground water levels that have been disturbed by additions from percolating water are very sluggish. The rate of these readjustments is influenced by the same factors of soil texture and physical condition that have been shown to affect the movement of water through subsaturated soil. In the absence of information to the contrary, we find it natural to assume that underground water seeks its level just as open water does. This is no doubt true, but it does so very slowly. If we make a survey of underground water conditions in an irrigated field, we find that the upper limit of the saturated zone is not level, but that in some places the free water stands much higher than in others.

THE ACCUMULATION OF UNDERGROUND WATER

The occurrence of soluble material in irrigated soils in harmful quantities may be taken as a definite indication that the irrigation water does not move downward through the soil. It is obvious that if there were a cumulative downward movement of water the soluble material would be carried away. It does not appear to be essential that this downward movement should be continuous or that any large proportion of the water applied to the soil should pass below the root zone. But it does seem certain that at least occasionally some water should pass on. Unless this is so it is inevitable that in time, either near or remote, the

soluble substances brought in by the irrigation water, together with those set free by soil disintegration, must accumulate to the point of harmfulness. Thus it may be said that for continued successful irrigation farming there must be a cumulative downward movement of water through the soil.

In the preceding chapters attention has been given to certain factors which contribute to a condition of the soil which hinders or prevents the normal downward percolation of water. There remains to be considered another situation which is equally effective in preventing such movement. This is the situation that exists when the subsoil is supersaturated with water. A large part of our irrigated land lies in the valleys of rivers where it is most convenient to divert water for irrigation. These valley lands are very commonly made up of sedimentary deposits from the main stream or its branches or from material eroded from adjacent high land. Only a part of the stream water is carried in the open stream bed. Another part, and often a very substantial part, is carried as underflow below the stream bed and under the adjacent valley lands. This underground water may occur as a continuous body extending to great depth and moving perceptibly though very slowly downstream, or it may be confined to certain underground channels of more permeable material, such as gravel or sand, which lie between islands of clay or fine silt in which no free or moving water is found. The diversion of stream water and its application to the valley lands very often results in adding to the supply of underground water to such an extent that the natural underground drainage ways are inadequate to carry it away. This results in raising the level of the saturated zone and necessitates opening new drainage channels if complete water-logging of the land is to be prevented.

In connection with a leaching experiment made on the Newlands Experiment Farm, Nev., in 1922, some observations were made which bear on this point. The field in which this experiment was conducted was divided into plats of approximately half an acre each. These plats were separated by parallel borders 85 feet apart. A large tile drain had been installed some years earlier along the south side of this series of plats, so that one end of each plat was just above the drain and the other end was less than 300 feet from it. There was a free discharge of water through this drain and the tile was seldom submerged. At the beginning of the leaching experiment the water in the sand box of the drain at the west end of the series of plats stood at 3,955.8 feet above sea level. At the east end of the series it stood at 3,955.5 feet. Though the drainage discharge varied somewhat during the experiment, the height of the water in the sand boxes changed but little. The ground surface in the plats ranged from just below 3,960 to 3,961 feet above sea level. Thus the water in the drain was about 5 feet below the ground.

The ground-water conditions within the plats were observed by means of open wells set in the borders between the plats. There was one line of wells across the north ends of the plats and another line across the south ends. These wells were cased with galvanized iron tubing 3 inches in diameter. Being set in the plat borders they were protected from direct filling when the plats were irrigated. During the progress of the leaching experiment it was possible to observe the height of the ground water as it was shown by these wells and to take samples from time to

time for analysis. The results of one series of these observations are shown diagrammatically in figure 7 for the north line of wells and in figure 8 for the south line.

These plats had been irrigated each week during August and September. Just after the irrigation that was completed on September 30 the water stood in the wells as shown by the upper line in each figure. Six days later, on October 5, the water stood as shown in the middle line in the figures, while nine days later, on October 14, it stood still lower. There are a number of points brought out in these diagrams that deserve mention. Possibly the most striking thing is that the upper limit of the saturated zone was not level or even approximately so. Then, too, the rate of subsidence was very different for the different wells. The variation in this respect was from 0.5 feet to 2.85 feet for the 15-day period. It may also be recalled that the south line of wells was located

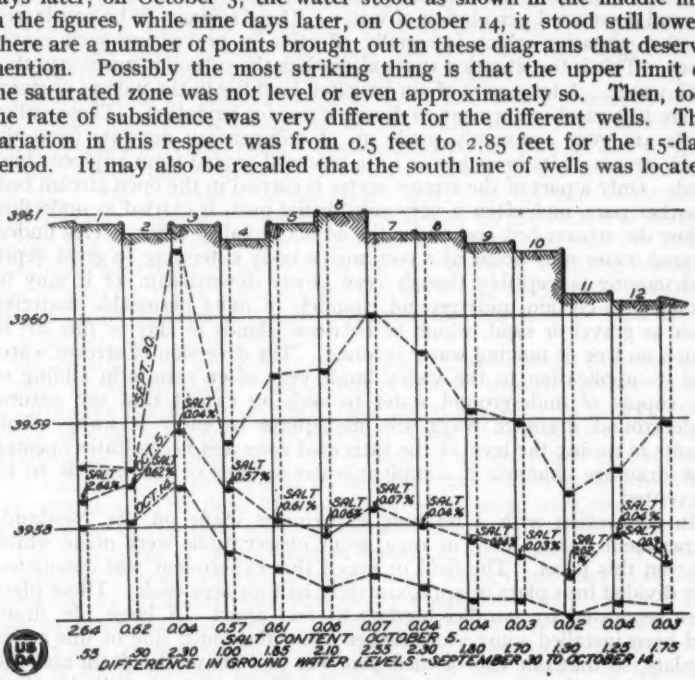

FIG. 7.—Ground-water levels, series Y north, Newlands Experiment Farm; irrigated Sept. 28 to 30, 1922.

only 15 feet from the tile drain in which the water was kept below 3,956. In only two of the wells in this line did the water drop below 3,957. The salt content of the water in these wells as determined on October 5 is shown on the diagram. These figures show that in quality also the water differed from well to well.

In the field in which these observations were made the underground water has been for years not more than 4 feet below the surface. While the soil in many large spots in the field has been so impermeable that irrigation water could not get through it, there have been other spots through which the water has soaked down readily. The lateral movement of the underground water has been very slow, in fact, almost imperceptible. It is probable that the evaporation losses from the moist soil when the water table has been high have resulted in concentrating the soil solution fully as much as it has been diluted by such contributions of irrigation water as have been made to it.

THE MOVEMENT OF UNDERGROUND WATER

The water that accumulates in the subsoil of an irrigated field is often thought of as similar to bodies of open water, such as lakes or ponds or as a continuous body of uniform quality and that if it is tapped by a drain its quality may be determined by sampling the drainage water just as we would sample a stream that flowed from a lake. If it were desired to know the quality of the water in a lake it would not be thought necessary to obtain samples from many different places in it. There might be slight differences in the quantity or character of the dissolved material as between the surface and the bottom of a lake or between points where springs or streams flowed into the main body of water. In an open body of water such differences are usually slight and they are still less in moving water such as streams. The movement of water results in thorough mixing,

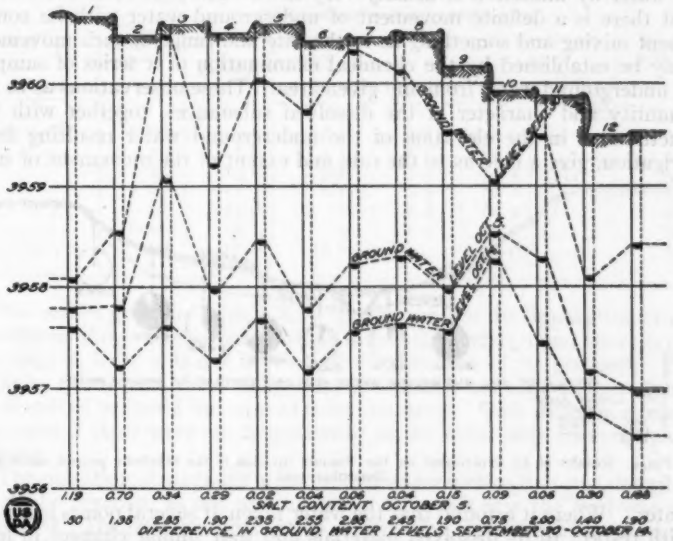

FIG. 8.—Ground-water levels, series Y south, Newlands Experiment Farm; irrigated Sept. 28 to 30, 1922.

so that a sample taken at one place in a stream is found to be much like a sample taken at another place in the same stream.

When we find that a drain is drawing water from the saturated subsoil of a field we are likely to assume that a sample of this drainage water may be taken as representative of the accumulated subsoil water of that field. As a matter of fact, a more detailed investigation of such a situation would be likely to show that samples of water obtained from the saturated subsoil in different parts of the field contained very different quantities of dissolved material.

The analogy of the drainage discharge from an irrigated field is not with a stream discharging from a lake but rather with a stream discharging from a swamp. In an open lake the water is free to move as in response to the wind, while in a swamp the movement of the water is restricted by islands and other barriers. A stream may flow through a swamp by way of a number of channels and not come in contact or mix with water

held in other parts of the swamp. When evaporation is going on rapidly the water in some parts of the swamp become much more concentrated than in the channels through which the water is moving freely. In much the same way the water applied to a field by irrigation enters and moves through the underground water in the more permeable channels and passes out in the drainage without necessarily mixing with the water held in the less readily permeable areas of the subsoil.

The actual course and rate of the movement of underground water is not easy to observe. Under some conditions it has been found possible to estimate the rate and direction of the movement of what is called underflow by putting into it at some point, as in a well, a quantity of some substance, such as a dye, which could be identified in samples taken from adjacent wells. Such investigations show that the actual movement of water by underflow is usually very slow. The fact as to whether or not there is a definite movement of underground water with its consequent mixing and something as to the rate and range of such movement may be established by the chemical examination of a series of samples of underground water from any given area. These observations as to the quantity and character of the dissolved substances, together with the fluctuations in the elevation of the underground water resulting from irrigation, give a clue as to the rate and extent of the movement of such

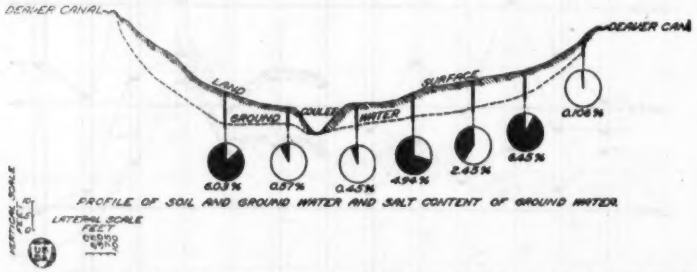

FIG. 9.—Results of an experiment on the Fraunie division of the Shoshone project, made in December, 1922.

water. Where it is found that the water taken at several points is similar with respect to its dissolved materials and that similar changes in level result from a common cause it may be inferred that there is a free movement. When these observations show pronounced differences it may be assumed there is very little movement or that the movement is confined to restricted zones or channels.

As an illustration of a situation in which there appeared to be very little movement in the underground water, a series of observations made on the Shoshone project, Wyoming, may be used. These observations were made by putting down a line of wells across the valley of a coulee around the head of which the Deaver Canal is located.[17] The canal forms a loop at this point which is crossed by the line of wells as shown in figure 9.

The wells were put down about 250 feet apart. The depth to water ranged from 2 to 10 feet below the land surface. The gradient of the plane of underground water is such as to indicate an absence of equilibrium and consequently a potential movement toward the coulee. In

[17] The writer is indebted to J. R. Iakish, of the United States Reclamation Service, for conducting the field work and collecting the samples of water.

the diagram, which shows a cross section of the ground in line with the wells, the position of the free water in each well is shown in relation to the land surface. The proportion of the dissolved solids, or salt content, of the water of each well is shown in figures below each well and shown also diagrammatically in the circles. It is apparent that the quality of this underground water is very different in the different wells. In the well at the extreme right, which is close to the canal, the salt content is very low. The next three wells show more salty water, while the wells on either side of the coulee are again less salty. The details of the analyses of the samples from these wells are shown in Table XXIV.

TABLE XXIV.—*Quality of underground water on the Shoshone project, Wyoming, from a series of shallow wells 250 feet apart; collected by Iakish and analyzed by Breazeale*

Well No.	Total solids, per cent.	Constituents as percentage of total solids.					Total acids.
		Ca+Mg.	$\frac{HCO_3}{2}$	Cl.	SO_4.	NO_3.	
11	6.031	4.9	1.1	2.8	58.0	5.1	67.0
12	.572	15.9	3.3	2.0	63.0	.9	69.2
13	.454	19.5	9.8	3.4	52.5	Tr.	65.7
14	4.948	12.5	1.1	2.9	62.0	.....	66.0
15	2.452	24.8	.9	1.4	64.0	.....	66.3
16	6.452	12.1	.4	1.4	63.0	.....	64.8
17	.106	16.0	22.0	Tr.	49.0	.....	71.0

The results given in Table XXIV tend to confirm the implication of the conditions shown in the figure, which is that the underground water is not moving; at least it is not moving in the direction of its gradient. The samples taken from these wells differ profoundly not only as to quantity of dissolved material but also as to its character. Such differences could not exist if there were much movement of the water with its consequent mixing.

The condition of stagnant underground water such as that just described might be regarded as not unusual when as in this case the land was not irrigated. The frequent application of irrigation water might be expected to result in time in obliterating such differences. The results of another series of observations made in an irrigated field on the Newlands Experiment Farm, Nev., show that even where a field is irrigated frequently and copiously and where there is a drainage system to carry away the surplus underground water the movement of the water is very irregular and its quality is equally variable, at least for a long time. The observations now to be presented were made in connection with the leaching experiment referred to in the preceding pages. The field included 6 acres divided into 12 plats, each 85 feet wide. These plats have been irrigated almost continuously since 1908, but much of the soil has been impermeable and crop growth has been very irregular. A view of the crop growth on one of the plats in this field is shown in Plate 2, A. In 1913 the accumulation of water in the subsoil of this field had reached such a point that drainage became essential and a tile drain was laid along the south side of the field about 5 feet below the surface. Notwithstanding persistent efforts to improve the condition of the soil by careful irrigation and good tillage, accompanied by manuring and the use of gypsum, this

field remains very irregular in productiveness. There has been marked improvement in some spots, but in others the soil is still difficult to work into good tilth and takes water very slowly.

In the early part of August, 1922, two series of wells were put down in this field. One line ran across the north side of the field and the other along the south side. The wells were set in the borders between the plats. The wells of the south line were set about 15 feet in from the tile drain.

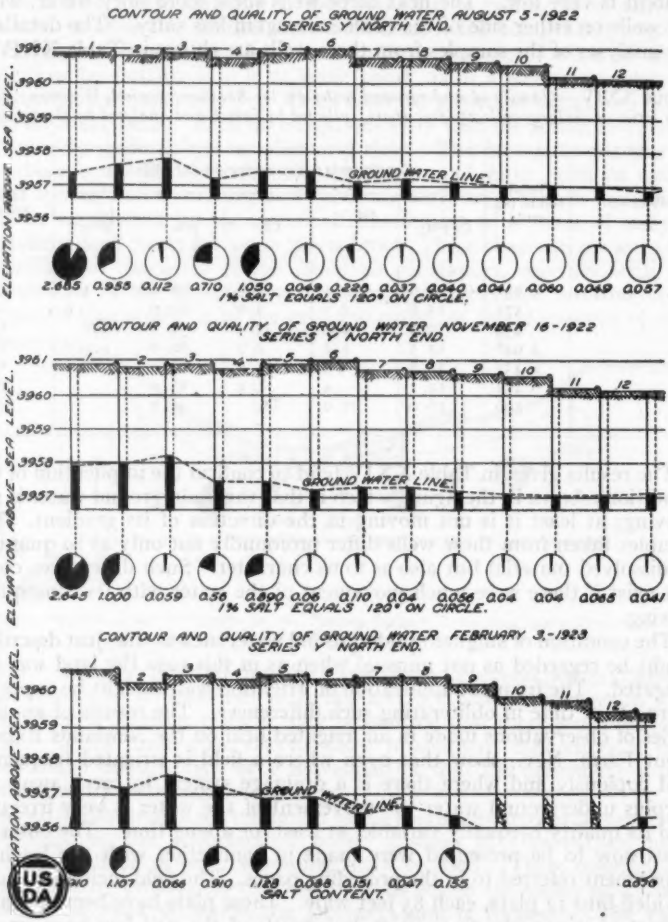
CONTOUR AND QUALITY OF GROUND WATER AUGUST 5-1922
SERIES Y NORTH END.
ELEVATION ABOVE SEA LEVEL.
3961
3960
3959
3958
3957
3956
1 2 3 4 5 6 7 8 9 10 11 12
GROUND WATER LINE.
2.685 0.955 0.112 0.710 1.050 0.069 0.228 0.037 0.040 0.041 0.060 0.049 0.057
1% SALT EQUALS 120° ON CIRCLE.
CONTOUR AND QUALITY OF GROUND WATER NOVEMBER 16-1922
SERIES Y NORTH END.
ELEVATION ABOVE SEA LEVEL.
3961
3960
3959
3958
3957
1 2 3 4 5 6 7 8 9 10 11 12
GROUND WATER LINE.
2.645 1.000 0.059 0.56 0.890 0.06 0.110 0.04 0.056 0.04 0.04 0.065 0.041
1% SALT EQUALS 120° ON CIRCLE.
CONTOUR AND QUALITY OF GROUND WATER FEBRUARY 3-1923
SERIES Y NORTH END.
ELEVATION ABOVE SEA LEVEL.
3960
3959
3958
3957
3956
1 2 3 4 5 6 7 8 9 10 11 12
GROUND WATER LINE.
1.107 0.066 0.910 1.128 0.088 0.151 0.047 0.135 0.050
SALT CONTENT.
US DA

FIG. 10.—Results of experiments on the Newlands Experiment Farm with wells 85 feet apart in the borders between the plats.

These wells permitted observations to be made from time to time as to the height of the ground water, and samples of this water could also be taken. The results of the first set of observations, made on August 5, 1922, are shown in the upper diagram of figure 10 for the north line of wells and in the same position of figure 11 for the south line. These diagrams show the height of the ground water in relation to the ground

surface and also the total salts as determined by electrical conductivity. The salt content is given in the figures and is also shown as segments of the circles. A full black circle would indicate 3 per cent of salt.

In the spring of 1922 the field had been sown to oats and alfalfa. Prior to the beginning of these observations it had been irrigated as the needs of the crop indicated. Irrigation was continued after the observa-

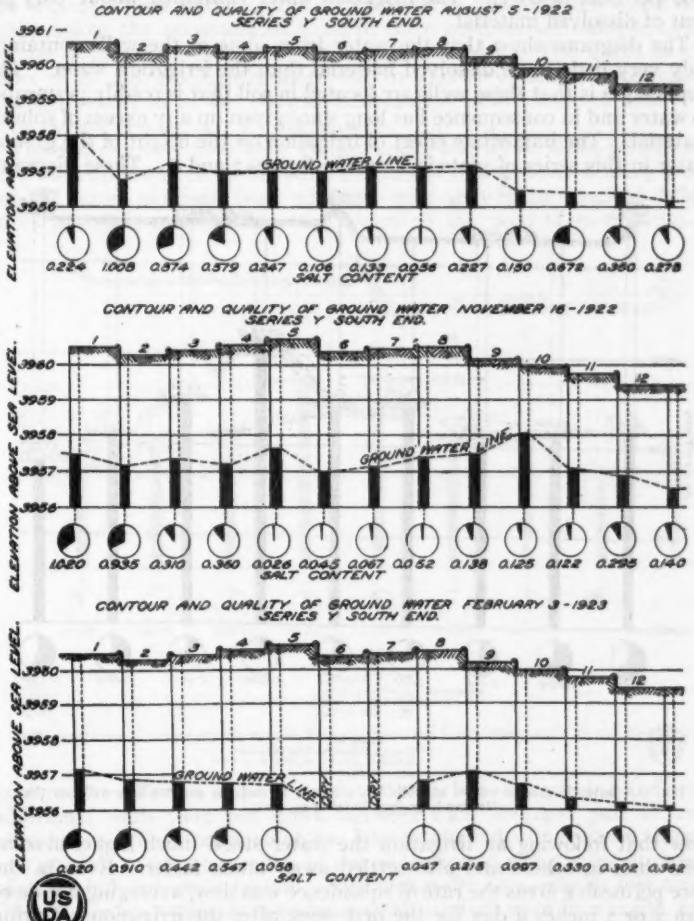

FIG. 11.—Cross section of 12 plats in the south end of the Y series at the Newlands Experiment Farm.

tions were begun, but with the aim of putting on all the water the land would take without injuring the young alfalfa. Nine irrigations were applied between August 5 and October 15. All of the water applied was held on the plats to soak in. In these plats the texture of the surface soil is extremely variable, ranging from coarse sand to a mixture of sand and clay in which the clay predominates. The subsoil conditions are no

less variable, but in putting down the wells it was found that coarse water-bearing sand could be reached, though in some places the clay was several feet thick. Although the wells all penetrated to the water-bearing sand it will be seen from the diagrams that the height of the ground water was not the same in all the wells and that its quality was very different. The range in salt content in the north line of wells was from 2.68 per cent to 0.037. The irrigation water contained about 0.03 per cent of dissolved material.

The diagrams show that the water from some of the wells contained only very little more dissolved material than the irrigation water. The implication is that these wells are located in soil that is readily permeable to water and in consequence has long since given up any excess of soluble material. The immediate effect of irrigation on the height of the ground water in this series of plats is shown in figures 7 and 8. These diagrams

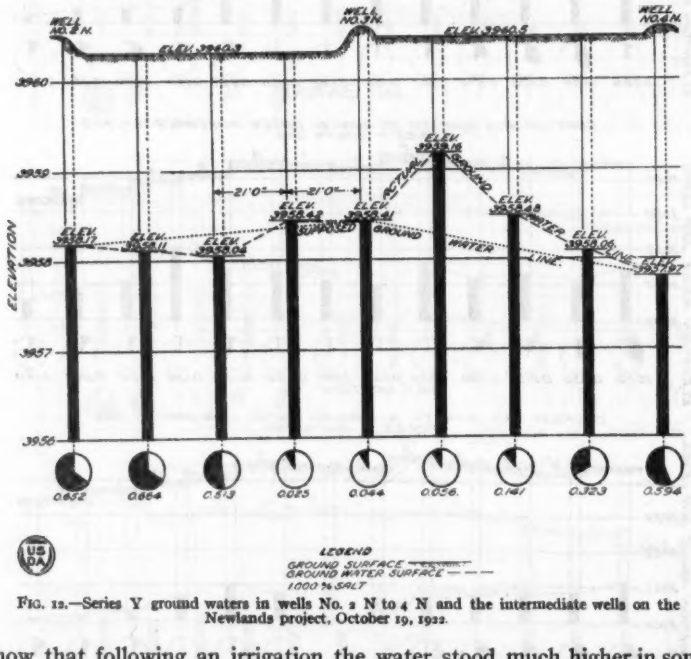

FIG. 12.—Series Y ground waters in wells No. 2 N to 4 N and the intermediate wells on the Newlands project, October 19, 1922.

show that following an irrigation the water stood much higher in some wells than in others and also settled away much faster. Even in the more permeable areas the rate of subsidence was slow, averaging not more than 2 or 3 inches a day for the first week after the irrigation. During the period of frequent irrigations in this leaching experiment when the water was applied as often as once each week the ground water remained about 1 foot higher than it had been before or than it subsided to after the close of the irrigation period.

The condition of height and salt content of the water one month after the final irrigation of the season is shown in the second diagram of figure 10, and figure 11. Although these plats had been copiously irrigated since the first of August and the drain had been discharging water continuously there is seen to be very little difference in the salt content of

each well as between the August and the November observations. There was no irrigation water used on these plats after October 14, and in fact none was used on the farm and very little was used on the whole project after that date. The discharge from the drain continued during the winter with a consequent lowering of the ground water. Observations made on February 3, 1923, gave results as shown in the diagrams at the bottom of each of the figures. In several of the wells the water had fallen below the accumulated sand in their bottoms and samples could not be obtained. These wells are reported as dry. The water in the other wells showed slightly more salt in February than in November. The differences as to salt content between the wells continued with very little change throughout the six months.

The wells in this field were 85 feet apart and all of them penetrated into what appeared to be the same stratum of coarse water-bearing sand, yet the water obtained from adjacent wells showed pronounced differences in salt content. This fact suggested the need of more detailed

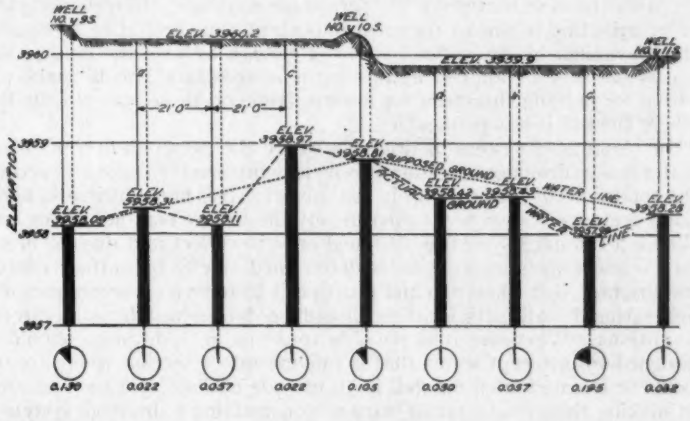

FIG. 13.—Series Y ground waters in wells Y 9 to Y 11 and the intermediate wells on the Newlands project October 19, 1922.

exploration. To this end one section of each line was selected and three additional wells were put down between each adjacent pair of wells already set. This was done at the close of the irrigation season when it was possible to obtain samples of the underground water without danger of direct inflow from irrigation. The new wells were only 21 feet apart. Observations as to depth to water and salt content were then made, with the results as shown in the accompanying figures. Conditions in the north line from well No. 2 to well No. 4 are shown in figure 12, and conditions on the south line from well No. 9 to well No. 11 are shown in figure 13. These results show that even when the wells are only 21 feet apart they show very pronounced differences both as to the height of the underground water and its salt content. The evidence presented from these two sets of field observations is supported by that from many others, all of which point to the conclusion that the movement of underground water is often very slight and nearly always irregular.

This lack of uniformity of the soil in many irrigated fields is very conspicuous. It tends to become more pronounced as the conditions resulting from the accumulation of soluble material become critical. One of the first signs of such trouble is the appearance of spots in the field where crop growth is abnormal. Spots of poor growth or bare spots appear and increase in size as the conditions become worse. These irregularities in the soil are manifested also in the underground water where conditions are such that it accumulates.

In the reclamation of saline soils the same diversity of conditions is found. In some spots improvement is marked and immediate; in others it is much slower. It seems evident that the water used for leaching as well as the water used for ordinary irrigation does not soak down into the soil at a uniform rate in all parts of the field. It is also apparent that the lateral movement of underground water to drainage ways, whether natural or artificial, does not proceed uniformly. There are channels or strata of permeable material in the subsoil often interspersed or cut off by other strata or barriers of less permeable material. In reclaiming land or in irrigating it, one of the most important aims should be to equalize the movement of the water. It is not enough to level the land so that the water may be applied uniformly; it is necessary also to make provision for holding the water for a longer time on those spots in the field where the soil is less permeable.

In planning a system of drainage where the accumulation of subsoil water makes drainage necessary it is no less important to take into account the conditions of permeability in the subsoil. It is not sufficient in laying out a drainage system to consider merely the surface contours of the land. Where a drainage system is designed only to collect and dispose of surface waste waters its location is determined chiefly by surface contour conditions. But when its chief function is to relieve an accumulation of underground water, its location should be determined by underground conditions. Whenever it is possible to do so, such drainage should be designed to intercept water that is moving into a section where trouble exists or is anticipated, as well as to provide outlets from such sections. In making the surveys preliminary to constructing a drainage system to prevent or relieve the accumulation of underground water, it is believed that chemical studies of the water should be helpful in locating the channels of free movement and consequently in placing drains.

COMPARISON OF IRRIGATION AND UNDERGROUND WATERS

It has been shown in the preceding pages that when a solution comes in contact with the soil, reactions may take place as a result of which constituents are exchanged. Both the solution and the soil are made different by these reactions. Furthermore, a large part of the irrigation water applied to the land is dissipated by evaporation or absorbed and transpired by crop plants, leaving the dissolved material in the soil. In consequence, the soil solution which accumulates as underground water in irrigated land is likely to be very different in concentration and composition from the irrigation water.

The comparison of the analyses of underground or drainage waters with those of the irrigation water affords a basis of understanding the reactions that are going on in the soil through which the water has passed. Such an understanding is much to be desired because it may make it possible to anticipate and to prevent some of the difficulties that follow

the accumulation of harmful quantities of soluble substances in the soil. Where conditions are such that it is possible to measure or to estimate the quantity of irrigation water used on a certain area of land and to measure also the drainage discharge from the land, analyses of the two waters make it possible to know whether the land is gaining or losing in salt.

Two examples may be cited as illustrations of this point. One is a valley containing about 100,000 acres of irrigated land so situated that the return flow of drainage water may be measured and sampled. Prior to the construction of a drainage system, the land on this valley was badly water-logged. The annual diversion for irrigation purposes aggregated 300,000 acre-feet of water which carried an average of 350 parts per million of dissolved solids. Upon the completion of the drainage system it was found that the aggregate annual drainage discharge was about 100,000 acre-feet of water, carrying an average of 1600 parts per million of dissolved solids. An acre-foot of water weighs 2,716,000 pounds, or 1,358 tons. With 350 parts per million of dissolved solids, an acre-foot of water carries 950 pounds. The incoming irrigation water carried to these valley lands 142,500 tons of dissolved solids, or nearly 1.5 tons per acre. The outgoing drainage, on the other hand, carried away 2.17 tons of salt with each acre-foot, or 217,000 tons for the year, or nearly 75,000 tons more than the irrigation water brought in. This situation indicates a marked decline in the salt content of the irrigated land. The general increase in crop yields in this valley also bears testimony to the improvement of the soil.

In another valley a similar study of conditions shows a different situation. The facts are substantially as follows: The valley includes about 53,000 acres of irrigated land. The annual diversion of water is 200,000 acre-feet, containing an average of 1,000 parts per million of dissolved solids. The annual drainage discharge is about 48,000 acre-feet, carrying an average of 1,410 parts per million of dissolved solids. Thus the irrigation water brings in 272,000 tons of salt annually and the drainage water takes out 92,000 tons, leaving a residue of 180,000 tons of salt in the valley. If this residue were distributed uniformly to the irrigated lands in the valley it would be equivalent to 3.4 tons per acre.

These two examples serve to show how one set of comparisons may be made between the quality of the irrigation and of the underground water. It is not always possible to make such comparisons because the percolating waters from irrigated land are sometimes lost into the country drainage and can not be measured or sampled.

In some situations where it is not practicable to measure the volume of the drainage discharge it is possible to obtain samples of the drainage water and by analysis compare its quality with that of the irrigation water. Such comparison makes it possible to judge of the reactions that are taking place in the soils. If no exchange reactions take place the drainage water should differ from the irrigation water only in being more concentrated as a result of the losses by evaporation or the use by plants. As a matter of fact, it is rather unusual to find a place where the underground water does not differ profoundly from the irrigation water both as to total solids and in percentage composition.

Where the irrigation water carries only a small quantity of total solids and these consist in large part of calcium and bicarbonate it is to be expected that as a result of the aeration and evaporation that takes place when the water goes on to the land these constituents

would be precipitated as calcium carbonate. The remaining solution would then show higher proportions of the other constituents. It is a matter of common observation that underground or drainage waters usually show lower percentages of calcium and of bicarbonate than irrigation waters. An example of these comparisons is shown in Table XXV. This table gives the composition of irrigation and drainage waters from three different irrigated regions. The composition of the irrigation water for each region represents the mean of several analyses. The drainage water from Newlands, Nev., is reported for two locations. One of these, drain Y 13, shows the mean of a series of analyses made on the drainage water from the field on the experiment farm which had been used for the leaching experiment discussed earlier. The percentage of calcium and magnesium in this water is very much lower than that of the irrigation water. The actual quantity of calcium is greater per unit volume of water, which would indicate that the difference in composition of the drainage water must be due in large part to its leaching action. The soil in the field where this drain is located is known to contain large quantities of soluble material the chief basic constituent of which is sodium. The water from the Fernley drain shows a higher proportion of calcium than that from the drain in field Y on the experiment farm. The soil of the Fernley district is known to be much more permeable to water than much of the soil of the experiment farm, and this condition may be associated with a higher proportion of calcium in its soluble constituents.

TABLE XXV.—*Comparison of total solids and percentage composition of irrigation and drainage waters from several irrigated sections*

Location of sample.	Total solids (parts per million).	Constituents as percentages of total solids.				
		Ca+Mg.	$\frac{CO_3+HCO_3}{2}$.	Cl.	SO_4.	Total acids.
Newlands, Nev.:						
Irrigation	158	10.1	34.0	9.5	23.0	66.5
Drain Y 13	3,440	1.3	23.6	6.0	28.0	57.6
Drain, Fernley	2,720	5.6	6.9	8.4	49.5	64.8
Huntley, Mont.:						
Irrigation	278	17.8	24.0	5.6	32.0	61.6
Drain 13	5,860	7.8	3.7	1.4	58.4	63.5
Bard, Calif.:						
Irrigation	960	17.3	14.5	11.2	37.8	63.5
Field wells	1,095	13.8	12.9	15.3	37.3	65.5

The comparison of the irrigation and drainage waters from the Huntley project shows that the drainage water contains lower proportions of the earthy bases, calcium and magnesium, than the irrigation water and also much less carbonate and chlorin. The indications are that in percolating through the soil it is taking up substantial quantities of sodium and sulphate. On both the Newlands and Huntley projects the drainage water is much more concentrated than the irrigation water, carrying 15 to 20 times as much dissolved material.

The waters reported from Bard, Calif., were taken on the Yuma project, which is irrigated from the Colorado River. On this project much of the irrigated land is underlain by a saturated zone that is directly

connected with the water of the river and may be regarded as a part of its underflow. The volume of this underflow is large, but its movement appears to be slow. The field wells from which the samples were obtained that are reported in Table XXV are located on the Bard Experiment Farm. The nine wells are so distributed over the farm of 160 acres as to give samples of the underground water for the whole tract. This underground water probably represents a composite of river underflow and of leachings from the irrigated fields. The figures reported are the means of six sets of analyses from nine wells. These results show a condition where the underground water differs very little from the irrigation water, either in total solids or in the composition of these solids.

The irrigation water that is applied to the land is dissipated in two or three ways. One part of it is absorbed by plants, another part is necessarily lost by evaporation from the soil, and where the quantity applied is more than the sum of these two losses the remainder percolates into the subsoil. The water that is absorbed by the plants is not ordinarily of the same composition as the soil solution; that is to say, the plant roots do not absorb the soil solution with which they are in contact. They absorb the water from this solution and with the water they take up only such dissolved constituents as are needed. This process is known as selective absorption.

It is obvious that crop plants do not absorb the soil solution as it exists in the soil. It is not uncommon to find that the soil solution in irrigated land contains as much as 1 per cent of dissolved mineral matter. It has been found (*3*) that the ordinary crop plants transpire as much as 500 pounds of water for each pound of dry matter produced. Of this dry matter only 10 per cent or less is mineral matter. From this it may be seen that the plant may transpire as much as 5,000 pounds of water and take into its system only 1 pound of mineral matter. This means that the water that is absorbed and transpired by plants leaves its dissolved mineral matter in the soil almost to the same extent as the water that is lost by evaporation from the soil.

When irrigation is so conducted that the water applied is all dissipated by plant absorption and by evaporation, the salts contained in the irrigation water are then deposited in the soil. Even where the salt content of the irrigation water is low the accumulation goes on and it is merely a matter of time until it reaches critical proportions. It is not uncommon to find irrigation waters in use that contain 1,000 parts per million of dissolved minerals. This is equivalent to 1.35 tons per acre-foot of water. As a basis of comparison it may be said that an acre-foot of soil which contains 15 per cent of moisture holds 300 tons of water. If this water holds in solution 1 per cent of mineral matter there would be 3 tons of such material in each acre-foot. From this it is clear that in the practice of irrigation it is essential that some part of the water applied pass downward through the soil, for it is only in this way that the excessive accumulation of salts may be avoided.

While many crop plants may obtain water from a soil solution which contains more than 1 per cent of dissolved mineral matter, it would appear to be advisable generally to keep the solution below that degree of concentration. In order to do this it follows that in applying irrigation water it should be the aim to use enough so that the proportion lost by percolation is large enough to offset the concentration due to evaporation and transpiration. Thus if the irrigation water contains 1,000 parts

per million of salt enough should be used so that 10 per cent of the quantity applied may percolate below the root zone.

In those irrigated sections where the subsoil is saturated, that is, where there is a water table not far below the surface of the ground, it is readily possible to determine the concentration of the soil solution. The accumulated underground water may be taken as representing that part of the solution that has percolated from the root zone. Where there is a drainage system which relieves the underground water, samples of the drainage discharge are usually more dilute than the average of the soil solution because there is nearly always some waste of irrigation water into the drains, and, furthermore, the downward percolation of water through the soil is not uniform. Where the soil is more permeable there is freer downward movement and less concentration through evaporation and transpiration.

It has been shown earlier in this paper that the detailed exploration of a continuous body of underground water shows great differences in concentration even within short distances. In general it seems safe to assume that where the concentration is high the movement of the water is slow, and, conversely, that low concentration indicates freer movement. Occasionally it is found that the salt content of the underground water is very high even where the surface conditions give no indication of it. Such a situation has been observed on the Huntley Experiment Farm in Montana. In one of the fields which has been continuously very productive a well was put down in the spring of 1922 for the purpose of sampling the underground water and noting its change of level in connection with a series of similar wells in other fields of the farm. In this field there were no surface indications of abnormal underground water conditions. The crops had been thrifty and uniform in growth and the yields had been large. In the early spring, when the well was put in, the water table was found about 10 feet below the surface. It was very salty, about 4 per cent. Repeated samples were taken and the well was pumped out to obtain fair samples. As the season advanced the level of the water rose until it stood within 3 feet of the surface yet the crop of silage corn on the field continued to thrive. Toward the close of the irrigation season the water receded, and during the following winter it stood again about 10 feet below the surface. The course of these changes in level and the salt content of the water as determined each month are shown in Table XXVI. It seems remarkable that good crop growth was possible on land where the water so close to the surface was more concentrated than sea water. The inference is that the underground water at this point represents the accumulated leachings for a long time and possibly from other places and that the rise of the water in this area resulted from pressures due to seepage or percolation in higher lands. The soil solution in the root zone must have remained more dilute than the water obtained from the well. The irrigation water used on this field contains only about 400 parts per million of salt and this with the rain and melted snow doubtless served to keep the solution in the surface soil below the critical limit, which for corn is probably not far from 1.5 per cent. The character of the solution obtained from the well in this field is shown in Table XXVII. Except for its higher salt content, this water resembles that obtained from the wells in adjacent fields and from a drain which serves the district in which the farm is located.

TABLE XXVI.—*Elevation and salt content of underground water in field O at the Huntley Experiment Farm, Montana*[a]

Date.	Elevation, water surface.	Depth to water.	Salt content.[b]
			Per cent.
1922.			
Apr. 28	2,966.4	10.0	4.25
May 31	2,966.7	9.7	4.20
July 1	2,967.6	8.8	4.17
Aug. 1	2,972.8	3.6	4.17
Sept. 3	2,971.0	5.4	4.37
Oct. 2	2,970.4	6.0	4.29
Nov. 3	2,969.3	7.1	4.28
Dec. 4	2,968.9	7.5	4.28
1923.			
Jan. 3	2,968.1	8.3	3.90
Feb. 5	2,967.7	8.7	4.00
Mar. 1	2,966.7	9.7	3.76
Apr. 3	2,966.8	9.6	3.90
May 1	2,966.0	10.4	3.79
June 1	2,966.2	10.2	3.46
June 27	2,968.0	8.4	3.24
July 25	2,970.9	5.5	3.13
Aug. 22	2,971.9	4.5	2.99

[a] The ground surface elevation is 2,976.4 feet above sea level.
[b] Determined by electrical conductivity.

TABLE XXVII.—*Composition of underground water in field O at the Huntley Experiment Farm, Montana, in July, 1923.*

PARTS PER MILLION

Total solids.	Ca.	Mg.	HCO_3.	Cl.	SO_4.	Total acids.
37,080	410	980	240	420	23,764	24,424

REACTING VALUES

37,080	20.5	80.5	3.9	11.8	494.0	509.7

PERCENTAGE REACTING VALUES

37,080	4.0	15.8	0.8.	2.3	96.9	100.0

[a] Collected by Hansen and analyzed by Brezeale.

THE ALKALINE CARBONATES

In the literature dealing with the problems of alkali soils the soluble carbonates occupy the center of the stage. "Black alkali" has been the *bête noir* of the irrigation farmer as well as of the investigator. Black alkali is usually defined as sodium carbonate while all the other salts in irrigated lands are referred to as white alkali. The carbonates of the alkali bases, sodium and potassium, are readily soluble in water. The carbonates of the earthy bases, calcium and magnesium, are practically insoluble in

water except when the water contains carbon dioxid. When calcium carbonate, for example, passes into solution in water containing carbon dioxid, it is customary to refer to it as calcium bicarbonate and to symbolize it as Ca $(HCO_3)_2$. This salt, if it exists, is unknown except in solution. When a solution containing it is boiled, the carbon dioxid is driven off and calcium carbonate is precipitated.

The carbonates of the alkali bases may be identified in and produced from nearly all soil solutions and drainage waters of irrigated lands. When the solution also contains carbon dioxid in sufficient quantity to render it neutral to an indicator such as phenolphthalein, these carbonates are said to exist as bicarbonates, for example $NaHCO_3$. It is possible to produce sodium carbonate or sodium bicarbonate by adding carbon dioxid to a solution of sodium hydrate. Both salts are common articles of commerce.

As it occurs in the soil solution in irrigated land, sodium carbonate has been regarded as the cause of serious injury to the physical condition of the soil and as highly injurious to plant growth. Much investigation has been directed toward discovering the circumstances of its formation and means of removing or neutralizing it. The salt has been thought of and referred to as a carbonate. This designation has focused attention on the acid ion CO_3 and diverted attention from its basic companion sodium. The acid ion CO_3 is known as a weak ion. This is probably due to the fact that carbonic acid, H_2CO_3, is inert as compared with such acids as hydrochloric and sulphuric. Carbonic acid is formed when carbon dioxid dissolves in water. The oxid of carbon is formed by the union of carbon and oxygen, as in burning charcoal. It may be released also by decomposition of the complex carbohydrates, such as plant tissues. It is assumed that most of the carbon dioxid that occurs in the soil solution is derived from the decomposition of organic matter in the soil.

The compound known as sodium carbonate is said to be a combination of a weak acid with a strong base. In water solution it reacts like the alkaline hydroxid NaOH except that when neutralized with a strong acid such as hydrocholoric acid half the sodium in solution as sodium carbonate forms a so-called acid salt. The reactions involved may be symbolized as follows:

(1) $NaOH+HCl=NaCl+H_2O$
(2) $Na_2CO_3+HCl=NaCl+NaHCO_3$
and
(3) $NaHCO_3+HCl=NaCl+H_2CO_3$
or
(4) $H_2CO_3=H_2O+CO_2$.

The reactions that occur in the soil when the soil solution contains sodium carbonate take place in the same way and to much the same extent with sodium hydrate. This fact permits the inference that it is the sodium and not the carbonate that causes the characteristic reactions. This inference appears to gain justification when considered in connection with the phenomena and the reactions involved in the exchange of bases in the soil. It has been repeatedly demonstrated, for instance, that when a soil is treated with a solution of sodium chlorid or sodium sulphate some of the sodium goes out of solution and an equivalent quantity of other bases come into solution. If the solution is then removed and replaced with pure water, the soil and the water show the reactions characteristic of the effect of sodium. The soil is deflocculated and the solution becomes alkaline. In view of these facts it may be justifiable

to approach the subject of the alkaline carbonates in their relation to the soil from the basic rather than from the acid side. In such an approach it becomes possible not only to avoid circumlocutions of language but also to see more clearly into the heart of the problem.

In dealing with the subject of alkaline carbonates in the soil solution it should be kept in mind that by the ordinary method of identification it is not the carbonate but the basic hydroxid that is actually determined (see p. 642). The method of titration gives not the quantity of CO_3 ions in solution but the quantity of basic ions that are in the solution in excess of the quantity of strong acid ions present. Thus, if one takes 50 cc. of N/10 NaOH to titrate with N/10 acid, it will require 50 cc. of the acid to complete the titration whether the solution is kept free from CO_2 or is saturated with it. In the same way with a soil solution, the quantity of acid that is required to complete the titration with methyl orange is the measure of the quantity of basic ions in the solution in excess of the quantity of ions of the strong acid radicals, such as chlorin, sulphate, or nitrate. The solution may contain much or little CO_2; it will have no effect on the quantity of acid required. The quantity of CO_2 in the solution does influence the reaction of the solution with respect to the indicators. Thus solution of NaOH in water free from CO_2 shows a pink color with phenolphthalein until the titration is completed. The addition of CO_2 to the same solution of NaOH reduces the quantity of acid required to titrate out the pink color of the phenolphthalein but not the quantity required to complete the titration with methyl orange.

In reporting the analysis of a soil solution it would be quite as correct and possibly less confusing to state the result of the acid titration in terms of excess of bases to strong acids as to give it in terms of CO_3 and HCO_3. This is, in fact, the custom of some analysts. It is not a matter of great importance what designation is used in reporting analytical results, but it is important to understand as clearly as possible what these designations mean. If it is clearly understood that the term carbonate, as used in connection with the soil solution, means the excess of bases over strong acids, there can be no valid argument against its use. There is, however, the possibility of misconception on the part of persons not thoroughly acquainted with the literature of the subject and the analytical methods used. Such persons might infer that the term carbonate implied carbon dioxid in solution.

The soil solution always contains carbon dioxid. This gas in the solution plays a most important rôle not only in the reactions between the solution and the soil but also in the reactions between the soil solution and the plants. It has been remarked above that calcium carbonate is practically insoluble in water that is free from carbon dioxid, but is very appreciably soluble in water containing that gas. There is ample evidence that the solubility of other soil materials also is influenced by carbon dioxid. An experiment recently conducted for the writer by J. F. Breazeale may be cited as an illustration. In this experiment two samples of the same soil were placed in large bottles and treated with water at the ratio of 10 parts of water to 1 part of soil. The mixture was shaken thoroughly and one sample was saturated with carbon dioxid, the other not being treated. Each day the supply of carbon dioxid was renewed in the treated mixture. After five days the solution was filtered off and titrated with acid and tested for calcium. The results of these tests are given in Table XXVIII, expressed in reacting values. That is, the reacting value of the acid required for titration is shown in the first column, and the reacting value

of the calcium is shown in the second column. The third column shows the difference between 1 and 2, which may be taken as the sum of the bases other than calcium existing in the solution in excess of the strong acids.

TABLE XXVIII.—*Effect of CO_2 in solution on the solubility of bases in the soil, expressed in reacting values based on the soil*

Sample.	r Acid required.	r Ca.	Difference.
1. Untreated	39.8	15.0	24.8
2. Saturated with CO_2	147.5	85.0	62.5
Increase from CO_2	107.7	70.0	37.7

In the absence of information to the contrary, it may be assumed that the CO_2 in the solution did not decrease the solubility of any of the material in the soil; in other words, that the increase of dissolved bases shown in the table represents a real increase in solubility.

Certain experiments recently reported by Kelley and Thomas (*11*) afford another illustration of the effect of dissolved CO_2 on the solubility of soil material. In their experiments they digested the soil for one hour with five times its weight of water partially saturated with CO_2. The results as reported by them are shown in Table XXIX, computed as reacting values. These results show that while only a part of the CO_2 added to the water of digestion is accounted for as carbonate in the solutions, there is a consistent increase in the quantity of total dissolved bases and in the dissolved calcium with increasing quantities of CO_2 used.

TABLE XXIX.—*Effect of CO_2 in solution on the solubility of bases in the soil, expressed as reacting values based on the dry soil* [a]

Soil No.	r CO_2 added to solution.	r Acid required.	Increase.	r Ca.	Increase.
905	None.	17.0	.....	0.25	.....
	50	34.5	16.5	6.25	6.00
	100	42.2	25.2	10.00	9.75
	200	60.5	43.5	20.25	20.00

[a] From Kelley and Thomas.

These illustrations of the effect of carbon dioxid in solution on the solubility of the soil material permit the inference that an abundance of carbonate in the soil solution may sometimes be beneficial rather than harmful. If the soil is rich in calcium carbonate, carbon dioxid in the solution brings the calcium into solution. Once in solution this calcium is free to react with and replace any sodium that may be combined with the soil. It has long been known that the application of organic matter to the soil tends to improve its physical condition. It is possible that this beneficial effect may be due in part to the enrichment of the soil solution in carbon dioxid from the decaying organic matter, followed in turn by the solution of calcium and the replacement of combined sodium by the calcium.

Such evidence as is available appears to indicate that the improvement of the physical condition of irrigated soil to the end of making it more readily permeable to water depends upon disposing of the sodium, whether this exists in the soil solution or in replaceable combination with the soil. It seems clear that it is the sodium and not the carbonate of black alkali that causes deflocculation and impermeability in irrigated soils.

THE REMOVAL OF SODIUM FROM THE SOIL

The sodium which causes trouble in irrigated soil must be thought of as existing partly as in readily soluble salts and partly as in combination with the soil material. The sodium salts that are readily soluble, such as sodium sulphate and sodium chlorid, may be removed from the soil by leaching, which is in effect merely replacing the solution in the soil by another solution applied at the surface. This is a very simple matter if the soil is readily permeable to the downward movement of water. The sodium that is combined with the soil material and which in such combination is only slightly soluble is the part that is difficult to remove from the soil. It is this combined sodium that causes deflocculation of the soil and consequent impermeability.

The removal of this combined sodium from the soil by leaching is possible only by replacing it with another base. It is possible to replace sodium from its combination with the soil with any other soluble base. There would be no point, however, in attempting to do so with potassium, for example, because such an exchange would not mend matters. Long experience has shown that calcium is the safest, most effective, and most easily available base to use in replacing sodium from the soil. The combination of calcium with the soil induces flocculation and makes for improved physical condition and permeability. Certain other bases, such as magnesium, iron, and aluminum, appear to produce the same effect.

A great variety of methods and of materials have been proposed for correcting the injurious effects resulting from the combination of sodium with the soil. Calcium sulphate, commonly known as gypsum, has long been recommended and extensively used. As a preventive of bad conditions it appears to be altogether satisfactory. As a remedy to be used when bad conditions have developed it is sometimes inadequate because it is only slightly soluble. Calcium chlorid and calcium nitrate are both very soluble, but the first is so deliquescent that it is difficult to handle except in solution and the second is relatively expensive. Iron sulphate is a by-product of certain manufacturing industries and is often to be had at prices that might justify its use in land reclamation. Aluminum sulphate is also a readily soluble salt and aluminum in solution actively displaces sodium from its combination with the soil and improves the physical conditions. With both iron and aluminum there is a possibility that when used in excess colloidal hydroxids may be formed which might cause temporary impermeability.

The assumption that the deflocculated condition of the soil is caused by the existence of alkaline carbonates in the soil solution has lead to some attempts to remedy this condition by the use of strong acids. Some experiments have been made with sulphuric acid, which is often very cheap, and elemental sulphur has also been used to some extent. The implication is that elemental sulphur when applied to the soil is oxidized through bacterial action and converted into sulphuric acid. This oxidation process takes place slowly, so that the product seldom reaches

injurious concentrations in the soil. Where the soil is rich in calcium carbonate, the use of either sulphuric acid or elemental sulphur may be expected to result in the solution of calcium with consequent beneficial effects.

It seems certain that when sulphuric acid is applied to the soil either directly or through the use of elemental sulphur, the reactions are not confined to the soil solution. For example, if it were found by analysis that a certain soil contained a certain proportion of dissolved bases in excess of the dissolved acids, that is, carbonates, and a quantity of sulphuric acid equal to that excess were added to the soil, it would be found that only part of the acid had displaced the carbonate from the solution and that the remainder had reacted with the soil to bring an additional quantity of bases into solution. If one were to extract a sample of the soil solution from that soil and add the acid to the solution the carbonates would be completely displaced and the solution made neutral, but when the solution remains in the soil this is not the case. This point deserves special emphasis because it has not been clearly understood. It has been natural to regard the soil as a mass of inert material holding a certain quantity of a solution, very much as a solution is held in a beaker, and that this solution could be titrated in the field in quite the same way as it could be titrated in the laboratory.

The experiments of Kelley and Thomas already referred to afford an excellent opportunity to illustrate this point that the acid reacts not only with the solution but also with the soil. One of these experiments involved the application of elemental sulphur to a sample of soil which was then moistened to optimum condition and kept at room temperature for 15 weeks. The soil was analyzed for all its water-soluble constituents before treatment. After treatment the water soluble CO_3, HCO_3, SO_4, and Ca were determined. The analyses before treatment showed that the total of the reacting values of the soluble acids was 169.2 per million of dry soil. The soil also contained calcium as calcium carbonate insoluble in water but soluble in 4 per cent HCl equivalent to a reacting value of 282 per million. Equal portions of the soil were treated with three different quantities of elemental sulphur, as shown in Table XXX, which also gives the quantities of the soluble constituents identified at the conclusion of the experiment.

TABLE XXX.—*Effect of elemental sulphur on alkali soil, the sulphur used and the solution constitutents being expressed as reacting values based on the dry soil.*[a]

Soil No.	Sulphur added.	r Acid required.	Loss.	r Ca.	Gain.	r SO_4.	Gain.
905	None.	17.0	.....	0.25	.....	74.0	.....
	12.5	10.3	6.7	1.70	1.45	86.1	12.1
	25.0	8.5	8.5	3.00	2.75	94.5	20.5
	50.0	7.6	9.4	6.60	6.35	120.7	46.7

[a] From Kelley and Thomas.

The results given in Table XXX show that a large proportion of the sulphur applied to the soil was oxidized into SO_4, which enriched the solution correspondingly. In the sample of soil to which 12.5 units of sulphur were added the dissolved sulphates were increased 12.1 units. The solution

extracted from this soil required less acid to neutralize it than the solution from the original soil by 6.7 units. From this it may be inferred that of the 12.1 units of SO_4 added to the solution, 6.7 units displaced CO_3 by combining with the bases already in the solution and that the remaining 5.4 units were united with bases newly brought into solution from the soil. Of the 5.4 units of newly dissolved bases calcium constituted 1.45 units.

In the sample to which 50 units of sulphur were added the solution was enriched by 46.7 units of SO_4, of which 9.4 units were absorbed in replacing CO_3 already in the solution, while of the remaining 37.3 units 6.35 may be assigned to the newly dissolved calcium and 31 units to other bases brought into solution from the soil.

It is clear from these results that of the sulphuric acid formed in this soil by the oxidation of sulphur only a part reacted to displace the dissolved carbonate, or, in other words, to neutralize the soil solution.

The conditions of this experiment were such that the carbon dioxid, liberated either from the solution directly or from the soil carbonates as a result of reaction with SO_4, could escape from the solution into the air. The solution and doubtless the soil also actually lost CO_2.

In another experiment Kelley and Thomas used sulphuric acid on the same soil, but instead of leaving the soil exposed to the air at optimum moisture content for 15 weeks they digested the soil samples for one hour by shaking them with five times their weight of water after adding sulphuric acid. After this digestion the solutions were analyzed for CO_3, HCO_3, and calcium. The results of these analyses are shown in Table XXXI computed as reacting values. This table also shows the quantity of acid added to each soil sample and the increase in calcium and other bases brought into solution by the acid, all expressed as reacting values per million of dry soil.

TABLE XXXI.—*Effect of sulphuric acid on alkali soil, the acid used and the solution constituents being expressed as reacting values based on the dry soil* [a]

Soil No.	r Acid added.	r Acid required.	Gain.	r Ca.	Gain.	r SO_4.
905	None.	17.0	.....	0.25	.....	74.0
	12.5	21.0	4.0	5.00	4.75	.....
	25.0	25.0	8.0	12.50	12.25	.....
	33.3	29.0	12.0	15.10	14.85	.....
	50.0	38.5	21.5	28.10	27.85	.....
	100.0	55.0	38.0	65.80	65.55	.....

[a] From Kelley and Thomas.

In this experiment the results show that the addition of acid to the soil solution did not decrease the carbonates, but instead the solution was actually more alkaline after the acid treatment than before. With the first sample reported in the table to which 12.5 units of acid were added, it is to be inferred that the solution was enriched in bases not only by the 12.5 units equivalent to the acid used but also by 4 units more combined as carbonates. This further increase of 4 units of dissolved bases may be explained by assuming that when the acid dissolved the soil carbonates, such as calcium carbonate, the replaced carbonate enriched the soil solution and thus brought still more calcium carbonate into solution.

These two experiments show very definitely that the addition of sulphuric acid to the soil solution in the soil does not give the results that would be expected if the soil were not present. They tend to confirm the view that the soil is not to be regarded as an inert mass in which a solution is suspended by capillarity, as water is held in a sponge, but rather that reactions are going on continually between substances in the solution and substances combined with the soil.

The present hypothesis is that the sodium that causes soil deflocculation and impermeability is the sodium that is combined with the soil and not the sodium that is in the soil solution. If this is correct, the treatment designed to flocculate the soil and improve its permeability should be aimed to replace the combined sodium from the soil by getting it into the solution and then to remove the solution. The difficulty can not be remedied by merely removing the solution.

A soil may be rich in combined or replacable sodium and consequently impermeable and at the same time contain a large proportion of calcium as calcium carbonate. With such a soil it is to be expected that any treatment that would bring into solution the calcium of the calcium carbonate would favor the reaction by which the combined sodium would be replaced from the soil and thus permit its removal by leaching. If a soil is found to be deficient in combined calcium, it may be necessary to treat it with calcium or some other base, preferably in the form of a soluble salt. In any case, the removal of combined sodium from the soil appears to require the substitution for it of another base, and if the soil is to be flocculated and its condition improved the substitution must be made by an earthy base.

The removal of sodium from the soil solution under field conditions is not a difficult matter if the soil has not absorbed so much sodium as to become impermeable. In other words, it is possible and not very difficult to prevent the accumulation of harmful quantities of sodium in irrigated soils. It is quite another matter to remove combined sodium from the soil in the field when as a result of such combination the soil has become impermeable to water. In dealing with sodium in irrigated soils an old adage may be used even with added emphasis. It would not seem extravagant to say that one ounce of prevention is worth a thousand pounds of cure.

SUMMARY

The effective supply of water that may be stored in the soil to last from one irrigation to the next is limited on the one hand by the field-carrying capacity and on the other by the inability of the plants to take water from the soil beyond what is known as the wilting point.

The soil may hold as much as 6 inches of water per foot of depth, but ordinarily its net effective storage capacity is not much above 2 inches per foot of depth.

The subsoil, which is usually more compact than the surface soil, may become saturated when it contains 5 inches or less per foot, and the addition of 1 inch of water to a saturated subsoil may raise the level of the underground water as much as 1 foot.

When irrigation water is applied to the soil it penetrates in part by flowing into cracks and also by way of the small spaces between the particles of soil.

The rate of the penetration of water into a dry soil is influenced not only by the general texture of the soil but even more by the physical reactions of the soil material to water.

The addition of water to a dry soil causes a perceptible change in color, so that it is possible in the laboratory to observe and measure the rate of penetration and to establish the fact that the rate of penetration is very different in different soils.

In a moist or saturated soil the movement of water, sometimes designated as percolation, may also be measured with a fair degree of accuracy.

The physical condition of the soil, which influences so profoundly the movement of water through it, is largely the result of chemical reactions that take place between the soil particles and the salts dissolved in the soil solution.

The character of the soil solution is a matter of fundamental importance in irrigated farming, not only because of its relation to the plant, but also because of its relation to the physical condition of the soil.

It is difficult to estimate the normal concentration or composition of the soil solution from samples obtained by digesting the soil with an excess of water.

The composition of the soil solution is determined by measuring its more important consitutents, which are identified as elements or ions and not as combined salts.

The important constituents ordinarily identified in the soil solution of irrigated lands include the earthy bases, calcium and magnesium, also the acid ions, carbonate, bicarbonate, chlorin, sulphate, and nitrate. The alkaline bases, sodium and potassium, are not usually identified quantitatively, but are estimated by difference.

The results of analyses of the soil solution may be stated in several ways, though for the sake of better understanding, it seems advisable to report only the constituents that have been identified.

There are great differences in the solubility of the various constituents of the soil, and these solubilities are influenced to some extent by the composition of the soil solution.

Changes in the concentration of the soil solution induce reactions between the solution and the soil, and consequently cause changes in the physical condition of the soil.

Changes in concentration also result in changing the balance of the solution constituents in relation to each other.

The soil solution is continually changing in concentration and in composition, and the soil takes part in these changes through reactions between the basic constituents of the solution and the bases combined with the soil.

The physical condition of the soil and particularly its permeability to water is largely influenced by the character of the bases that are combined with the soil. When the alkaline bases, sodium and potassium, predominate the soil is deflocculated and impermeable. When the earthy bases, calcium and magnesium, are in excess the soil is flocculated and permeable.

When saline soils are leached to reduce the concentration of the soil solution it is often found that they become impermeable to water. This condition is due to the effect of the alkaline bases combined with the soil, which causes deflocculation to take place when the salts of the strong acids, sulphate and chlorin, are removed from the solution.

Where the subsoil of an irrigated field is saturated with water or contains strata or barriers that are slowly permeable to water, effective leaching of the soil is seriously hindered because of the accumulation of underground water.

The lateral movement of underground water, like the downward movement of water through the soil, is subject to great variation, depending upon local conditions, and the quality and concentration of the solution are also highly variable even within the same field.

The comparison of the quality and concentration of underground waters from different parts of the field with those of the irrigation water permits a better understanding of the drainage requirements of the soil than is possible from observing only the depth to the underground water.

The injurious effects that have been ascribed to sodium carbonate or "black alkali" in irrigated soils appear to be due to the sodium rather than to the carbonate, and sodium in solution even when associated with the stronger acids combines with the soil and ultimately causes deflocculation and impermeability.

The readjustment of the relative proportions of sodium and other bases in an impermeable soil, to the end of improving the physical condition, depends upon replacing the sodium with another base, such as calcium or aluminum, which, when combined with the soil brings about a flocculated and permeable condition.

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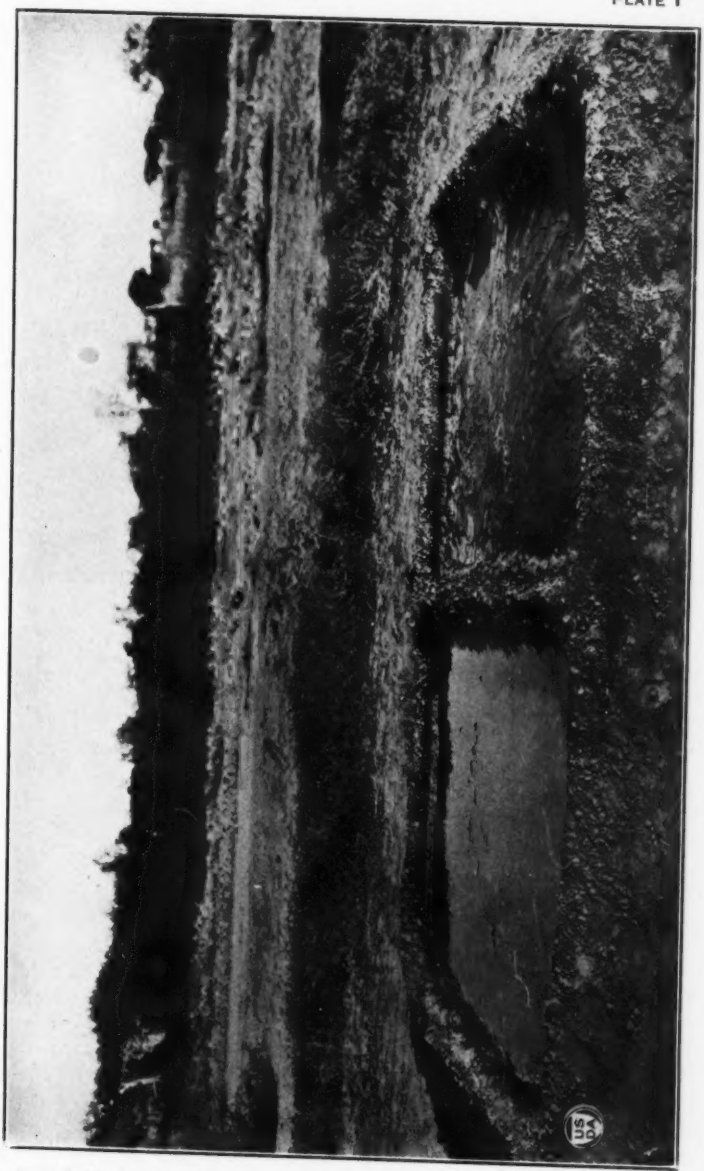
PLATE 1

The effect of aluminum sulphate on the penetration of irrigation water. The plat at the right was treated with aluminum sulphate at the rate of 5 tons per acre, but the plat at the left was not treated. Both plats were given the same quantity of water. Photographed 54 hours after the water was applied; Sacaton, Ariz., November 18, 1921.

PLATE I



A

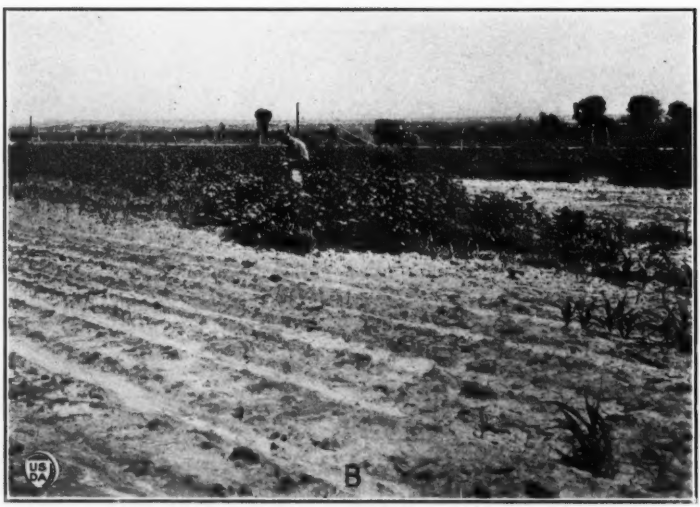

B

PLATE 2

A.—Irregularity of crop growth on a plat in field Y, at the Newlands Experiment Farm, 1922.

B.—Irregularity of crop grown in cotton field on the Yuma reclamation project, Arizona, 1919.

AN APPLE STEM-TUMOR NOT CROWNGALL[1]

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There are many kinds of apple-tree outgrowths or stem deformities; some are due to winter injury, some to weak variety conditions, some trees have short internodes, others, swellings of internodes or nodes. The type referred to in this paper as stem-tumor is the outgrowth with masses of rootlike projections or, as it occurs on some varieties of apple trees, an outgrowth with a smooth or nearly smooth surface. The outgrowths vary in size from small warts (Pl. 2, A) to tumors 2 to 6 inches in diameter, though they project scarcely more than one-half inch beyond the surface of the stem (Pl. 1, C). On some trees the bark remains comparatively smooth and the tumors do not reach a breadth of more than two or three inches (Pl. 3, B); but usually the bark breaks and masses of aborted roots appear, giving a roughened budlike surface to the outgrowth. The tumors of the bud type increase in size readily and in time the bark may become black and rough and broken if the tree is a very susceptible one. This may extend along an entire limb (Pl. 2, C). The budlike type is the more common.

These tumors are similar in macroscopic details to tumors produced by artificial inoculation with pure cultures of *Bacterium tumefaciens*. Furthermore, crowngall and hairy-root are widely prevalent on apple trees. Accordingly, although some entomologists[2] have referred to infestation by woolly apple aphis as capable of resulting in galls or warty swellings on twigs, limbs or trunk of apple trees, nursery inspectors, nurserymen, orchardists, plant pathologists and entomologists have in general referred to this type of outgrowth as aerial crowngall. However, this so-called aerial crowngall, of which Plate 1, A, is a good representation, is seldom, if ever, caused by the crowngall organism under natural conditions.

Since 1906 the writer has been concerned with crowngall on various hosts and during this period the attempts to isolate *Bacterium tumefaciens* from apple stem-tumors always have been unsuccessful, but as the tumors resembled the hairy-root type of crowngall as it occurs on apple roots it was believed that the disease was a form of crowngall. In 1923 the writer began a more critical study of the disease.

Some of the material used was received from several different States, and some of it was collected near Washington by the writer, so that there was ample material in good live condition for the platings. Platings were made from tumors just starting to form, and in all stages of growth and development, the largest being 6 inches in diameter.

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[1] Received for publication Dec. 20, 1923.

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ORMEROD, Eleanor A. HANDBOOK OF INSECTS INJURIOUS TO ORCHARD AND BUSH FRUITS WITH MEANS OF PREVENTION AND REMEDY. p. 1-6. London. 1898.
STEDMAN, J. M. THE WOOLLY-APHIS OF THE APPLE. *In* Mo. Agr. Exp. Sta. Bul. 35, p. 40. 1896.
THEOBALD, Fred. V. THE INSECT AND OTHER ALLIED PESTS OF ORCHARD, BUSH, AND HOTHOUSE FRUITS AND THEIR PREVENTION AND TREATMENT. p. 141-153. London. 1909.

During the year 1923, 378 plates were poured. These plates were made from 23 different lots of material and included 38 sets. Previous to 1923, during the years 1909 to 1922, inclusive, there were 120 plates poured from apple stem-tumors, 12 sets from 9 different lots of material. No single colony of *Bacterium tumefaciens* appeared. There were some fairly constant bacterial colonies closely resembling crowngall colonies which appeared on the plates and these were tried out in 1923 on Early Harvest apple trees, a variety known to be susceptible to this disease. The trees were inoculated in May in 138 young growing stems, using 8 different colonies; controls were held at the same time and the inoculations were made in two orchards 18 miles apart. The following greenhouse plants, known to be susceptible to *Bact. tumefaciens*, were also inoculated with these 8 colonies: 30 Paris daisies, 31 young tomato plants, 16 Ricinus, 12 Bryophyllums, 5 tobacco plants and 6 geraniums. The results with these plants were all negative.

In the case of the apple trees under observation, swellings occurred in the axils of leaves of branches where there were neither inoculations nor control pricks. These swellings were small; even as late as October they were only 3 mm. to 1 cm. in diameter. Five swellings which occurred on the main stem of a young tree were much larger; these varied from 1 to 2½ cm. in diameter. The large outgrowths had the typical budlike projections of apple stem-tumor. These places were not inoculated nor were any places on the main stem of the tree inoculated. The only stimulating agent present in October which might be held responsible was the woolly apple aphis (*Erisoma lanigera* Hausmann) a colony of which was on each of these swellings. The tumors had been noted in July when they were smaller, and the aphis was also on them at that time. These tumors were so fresh and soft that the writer, thinking it might be a natural infection of crowngall, cut off portions of two of them expecting to isolate the crowngall organism very readily from these pieces. It could not be done.

Woolly aphids were in the axils of the leaves where axil swellings occurred (Pl. 3, A). The inoculated places were carefully examined and in all of the 138 inoculated stems there were only three outgrowths. These three places were in the axils of leaves and were covered with woolly aphids. Some of the small axil swellings on these Early Harvest apple trees were cut off, and also pieces of the large stem-tumors, a second time. Platings were made from both lots but neither the crowngall nor any other constant organism appeared on the plates.

In an orchard where stem-tumors were quite prevalent 44 trees were examined at the roots and woolly aphis root galls found on 34 of them; 32 of these rootgalled trees had stem-tumors, and only one tree was found with stem-tumors which did not also have the aphis rootgalls. On the roots of one of the trees most severely affected with stem-tumor the woolly aphis was present in great numbers and had produced root-tumors (Pl. 3, C). The same insects were present on the branches also and were abundant on the stem-tumors (Pl. 3, D). No crowngall was found on any of the trees.

Not all varieties of apple trees appear to be subject to these stem-tumors. The character of the soil and cultivation may have much to do with this, but some varieties, as the Early Harvest, seem susceptible under any conditions. Very susceptible varieties which have come under the observation of the writer are the following: Early Harvest, Wagoner,

Martin, Buckskin, Grimes, Ben Davis, Barnes' Best, Ensee. There were 10 varieties in an orchard examined which were less susceptible than the above named in varying degrees. All had woolly aphis rootgalls. The stem-tumors varied in size and number (Pl. 2, B and C) and on some trees there were indications that the tumors had kept on developing for some years; then some change in conditions took place and the newer branches were clean, since few or no tumors had formed during the last years. Four apple varieties in this orchard, Titavka, Loy, Bethlemite and Van Hoy, had no stem- or root-tumors and did not seem susceptible. The first three varieties had no woolly aphids on them anywhere. Although Van Hoy had some of the woolly aphids on the young twigs there were no swellings.

In a young orchard consisting of 58 apple trees, two of which were the Early Harvest variety, these two were the only ones with the woolly apple aphis on the stems and the only ones with stem-tumors.

Other varieties, such as the Chenango, Spitzenberg and King, affected with stem-tumors, were received from various parts of the United States.

A bad feature of the numerous stem-tumors on apple trees is the opportunity it provides for secondary organisms to get into the stem and ultimately cause more damage than the stem-tumor itself. The tumors are composed partly of soft cortex tissue which wood-invading insects can feed on and get through into the deeper portions of the stem, continuing their work of invasion throughout the year and forming great holes. The movement of sap is, of course, interfered with, which in turn affects the whole life processes of the tree. The breaks in the surface of the bark where the tumors push through likewise offer an entrance for the pear-blight organism, *Bacillus amylovorus*, which also causes greater damage than the stem-tumor (Pl. 2, D).

From the report of the results of Dr. J. J. Taubenhaus' work [3] with apple stem-tumor, it seems that *Bacterium tumefaciens* may occasionally cause stem-tumor on apple tree perhaps similar in appearance but of different origin from that described in this paper.

It is theoretically possible for *Bacterium tumefaciens* to produce tumors naturally on apple stems as well as on the crown and roots, for galls have been produced artificially by inoculating apple stems with *Bacterium tumefaciens* (Pl. 1, B). So far as the writer's observation goes, this organism confines its work in nature to the production of galls and hairy-roots on both crown and roots of apple trees. The cases of apple stem-tumor from various parts of the United States examined by the writer did not contain *Bact. tumefaciens* in a single instance.

CONCLUSIONS

Outgrowths on stems of apple trees herein described, and heretofore generally believed to be due to infection by *Bacterium tumefaciens*, the organism producing typical crowngall, are not secondary outgrowths from tumor strands nor are they primary infections of the crowngall organism. Although such conditions have not been observed by the writer, it is possible that in some regions there may be aerial tumors for which the crowngall organism is responsible.

[3] ADAMS, J. F. DISEASES OF FRUIT AND NUT CROPS IN THE UNITED STATES IN 1922. U. S. Dept. Agr. Bur. Plant Indus. Plant Disease Bul., Sup. 28, p. 308. 1923. (Mimeographed.)

The root projections on the stem-tumors carrying darkened and usually infected tissue deep into the tumors, and the hard woody nature of the outgrowths themselves, make isolations difficult. When *Bacterium tumefaciens* did not appear on the isolation plates, it was thought due to the dry or old condition of the material used, and it was not until 1923, when young, tender stem-tumors were studied along with older tumors, that the conclusions given in this paper were reached.

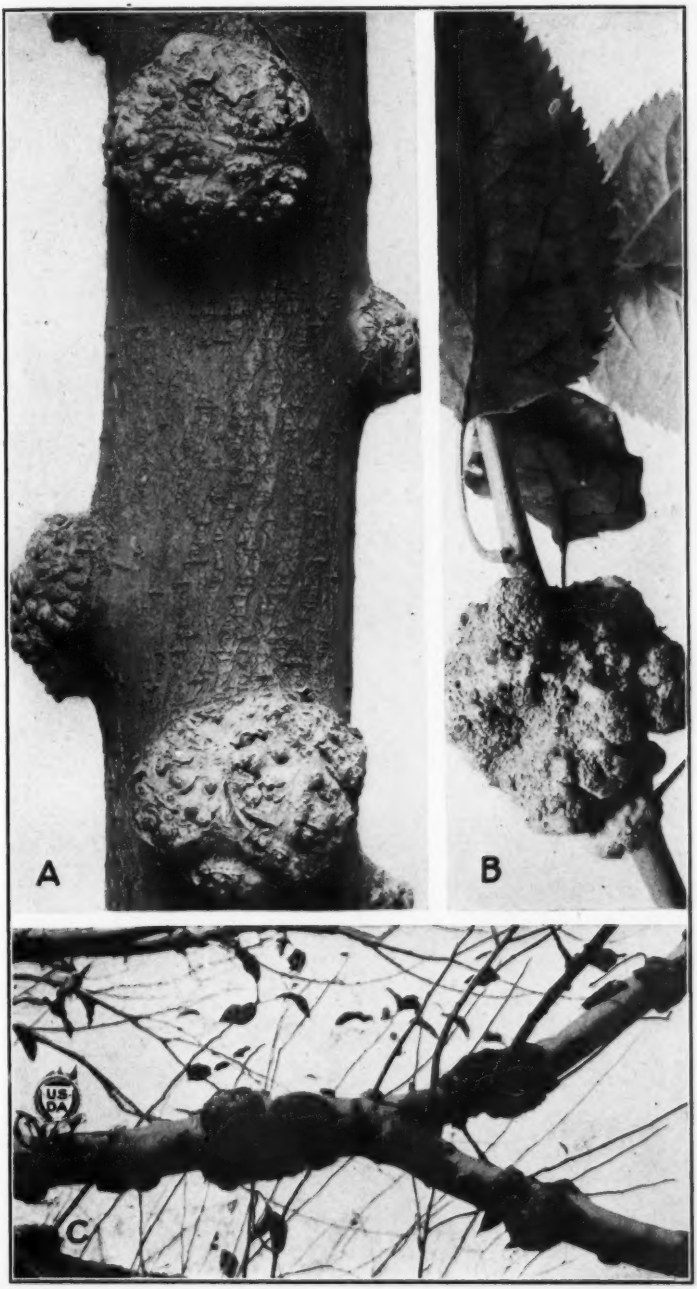
Whether or not the woolly apple aphis is the primary cause of the stem-tumors on mature apple stems herein described has not been within the scope of this investigation. There is a possibility, of course, that an organism may be transmitted by the aphids into the stems of apple trees—an organism which undergoes a change through insect transmission and which on that account does not retain its ability to infect after it has been isolated. This might explain the appearance on agar plates of colonies isolated from apple stem-tumor which at first so strikingly resemble the crowngall colonies, but lose this resemblance when cultured artificially and which also fail to infect when inoculated into apple trees and other plants susceptible to *Bacterium tumefaciens*. Had crowngall-infected apple trees been in the neighborhood of the apple trees affected by stem-tumor, the writer would be inclined to give attention to this possibility. But she found none. It seems, therefore, that *Bact. tumefaciens* is eliminated from the consideration.

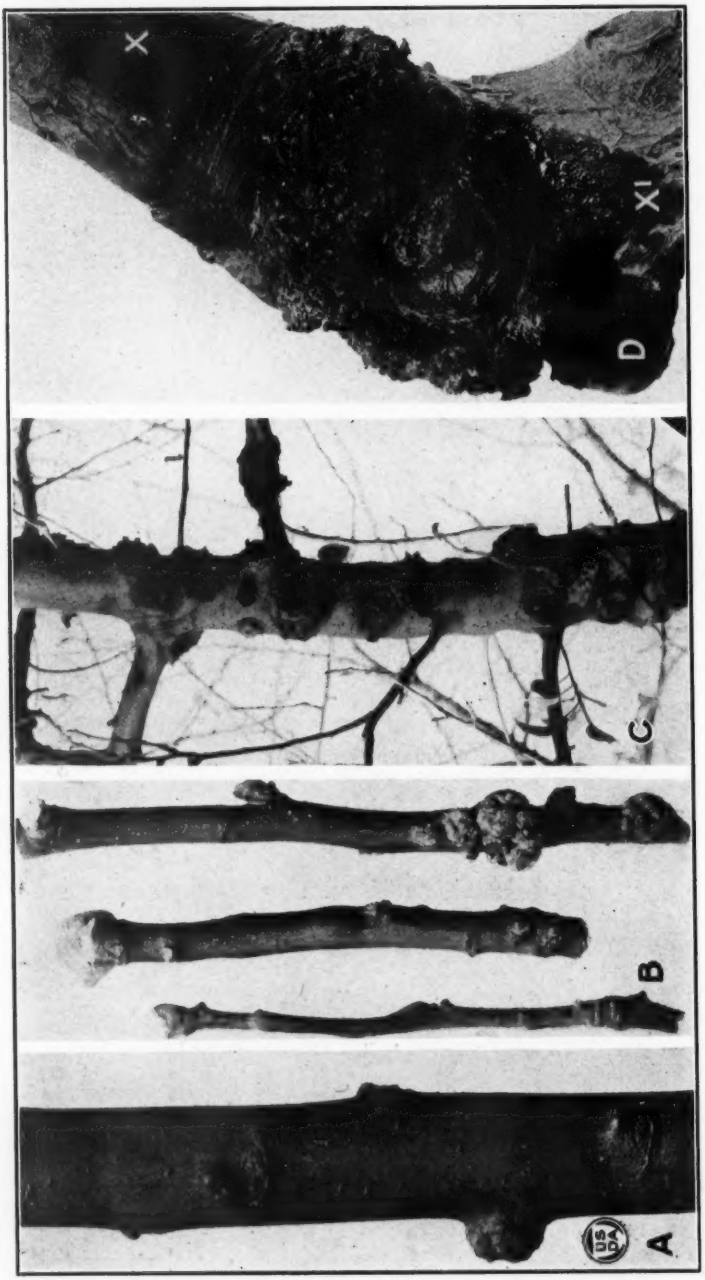
PLATE 1

A.—Stem-tumor of apple tree from West Virginia. Natural size. Photographed April 22, 1923. No crowngall organism could be isolated from these tumors.

B.—Crowngall on apple stem produced by inoculating with *Bact. tumefaciens* (peach strain). Inoculated March 11, 1908. Photographed August 10, 1908; three-fourths natural size.

C.—Old and young stem-tumors on Wagoner apple tree, Virginia; one-fifth natural size.


A
B
C
U.S. DA



A.-
Virgi
B.-
three
from
C.-
roots
D.-
at X

PLATE 2

A.—Early stage of apple stem-tumor on Chenango Strawberry apple tree, West Virginia; natural size.

B.—Young stages of stem-tumor on Buckskin apple tree. The three pieces show three different years' growth of tumors on the same stem. Natural size. Plated from the largest outgrowth, but no crowngall organism was present.

C.—Older stage of stem-tumor on Buckskin apple tree, showing masses of aborted roots; one-fifth natural size. Same tree as B.

D.—Old stem-tumor on Spitzenberg apple tree from Oregon showing pear blight at X and X' as a secondary disease. Natural size.

PLATE 3

A.—Beginning of apple stem-tumor at X, and X'. Woolly apple aphis abundant at these places. Early Harvest apple tree, Maryland.

B.—Type of stem-tumor on Martin tree, which shows few or no masses of aborted roots. At X a few are ready to burst through the bark. Platings were made from tumor X. No crowngall organism was present. Woolly apple aphids were on these tumors; one-third natural size.

C.—Woolly apple aphis *root* galls on Buckskin apple tree; natural size. Same tree from which stems B and C of Plate 2 were taken.

D.—Early stage of apple stem-tumor on Buckskin apple tree from Virginia. $\times 5$. Negative platings were made from these also. Note presence of woolly apple aphis.

X
X
X
A
B
X
C
D

MORPHOLOGICAL CHARACTERS OF ALTERNARIA MALI ROBERTS[1]

By JOHN W. ROBERTS

Pathologist, Fruit-Disease Investigations, Bureau of Plant Industry, United States Department of Agriculture

Some years ago *Alternaria mali* was described by the writer (*16*)[2] and shown to be involved in a peculiar spotting of apple leaves. *Alternaria mali* does not originate these spots, but, gaining entrance through areas killed by *Physalospora cydoniae* (*Sphaeropsis malorum*), by chemicals such as sprays, or by other means, enlarges the dead spots, giving them a peculiar and characteristic appearance. A spot thus formed consists of the original dead area with semicircular or crescent-shaped enlargements about it (Pl. 1, B). One might conceive of such a spot as being formed by infections taking place indiscriminately within the tissues of the original dead area. The fungus growing at equal pace in all directions from each of these infection centers would occupy circular areas, only part of which would project beyond the original spot. Where there is a single infection, in the center of a circular spot, the enlargement appears as a differently colored zone surrounding the original spot and concentric with it. By means of new infections the increase in size may be such that one spot may involve almost an entire leaf, appearing as a more or less circular (original) spot surrounded by consecutive crescent-shaped enlargements. The striations or zones within the spots greatly resemble those produced by species of Alternaria on the leaves of other hosts.

Crabill (7) does not agree that *Alternaria mali* is the cause of the enlargement of spots initiated by *Physalospora cydoniae*. His inoculation experiments were apparently very few in number and his results indecisive. Of the writer's work Crabill states: "His photographs, however, show that the enlargements produced by artificial inoculation with *A. mali* are not at all typical. They are too uniformly spreading to resemble the clear-cut crescents of the typical frog-eye spot." Yet these photographs show a remarkable resemblance to figure 4 of his bulletin, labeled "Frog-eye leaf spots as they appear in midsummer." As a matter of fact, both Crabill's photographs and those of the writer would have shown the crescents more clearly cut had the leaves been allowed to become older and dry before photographing. The writer's experiments involved more than 3,000 spots, and the results in all experiments involving *Alternaria mali* were quite decisive. The fungus was found constantly associated with characteristic spots on apple leaves from Virginia, Maryland, Tennessee, Arkansas, and Missouri.

THE GENUS ALTERNARIA

The difficulties underlying attempts to identify species of Alternaria are appreciated by all those who have ever undertaken the task. Many

[1] Received for publication February 20, 1924.
[2] Reference is made by number (italic) to "Literature cited," p. 707–708.

of the species are described so vaguely or so briefly that almost any member of the genus could be placed within them. Many investigators, finding an Alternaria on a new host, have made a new species of it and published a brief description wholly inadequate for purposes of positive identification.

Elliott (*9*) has done much toward the establishment of the generic limitations of Alternaria and has sorted out some of the species into groups. He states: "No final disposition of the present specific names of Alternaria and Macrosporium can be made without a study of authentic specimens of each species. Most of the descriptions are far from being complete or definite enough to permit their being used for this purpose." Until such work as Elliott suggests is done, the identification of species of Alternaria must in most cases be quite uncertain.

Elliott's emended description of the genus is such that *A. mali* undoubtedly belongs within it. His description is as follows: "Alternaria Nees. Conidiophores solitary or fasciculate, erect or subdecumbent, simple or branched, generally short, colored. Conidia muriform, often with few longitudinal septa, ovate, obclavate, or elongate, always with more or less definitely pointed apex, often long-beaked, colored, under favorable conditions forming chains. (Ex. *A. tenuis*, type of the genus.)"

The writer has studied *Alternaria mali* as found growing in dead spots on apple leaves and as cultivated on artificial media. In addition, *Alternaria tenuis*, from Europe, and species isolated from the leaves of lilac, forsythia, and blackberry and from the fruits of apple, cranberry, and blueberry have been grown on artificial media and studied.

All these forms, while resembling one another in many respects, revealed many points of difference. In some species the hyphae were almost colorless, forming a thin scarcely perceptible crust over the surface of a plate of corn-meal agar with an exceedingly scant production of conidia and no aerial hyphae. Others formed a dense, nearly black crust with a copious production of conidia and no aerial hyphae. Still others produced a black crust with abundant conidial production at its surface and an abundance of more or less flocculent aerial mycelium or a greenish-gray aerial mycelium so dense as to form a thick carpetlike growth over the surface of the culture medium. A few produced an abundance of dirty white aerial hyphae with a very scant growth in the medium or along its surface and a very scant production of conidia.

In the species studied the conidia conformed to the generic description, that is, they were ovate, obclavate, or elongate. In most of these obclavate conidia predominated, but ovate conidia were found in cultures of all except one form which produced elongate forms exclusively. In the species producing practically no aerial hyphae, elongate conidia predominated. While the surfaces of the spores were usually smooth, in some forms verrucosity was quite common. An entire conidium or only a part of it often possessed a verrucose surface. If only a part of the conidial wall was verrucose, it was in a strip or band at right angles to the long axis of the conidium. Verrucosity or absence of verrucosity was not so much a difference between conidia as between chains of conidia, the conidia of individual chains usually being all verrucose or all smooth-walled. The presence or absence of verrucosity appears to be due to highly localized conditions of the immediate environment, if one may judge from selection experiments reported upon later in this paper.

The conidia of all the species were produced in chains with the narrower end distal. De Bary (*1*), Jones (*11*), Elliott (*9*), and many others found

this to be true of the species studied by them, and that the conidia of all species of Alternaria are so arranged is generally believed. However, in examining published illustrations of Alternaria, even of quite recent date, one finds drawings in which the broader end of the conidium occupies the distal position. It would be interesting to know whether or not such forms really exist.

At the distal end of each conidium, except quite frequently the last one formed in the chain, there is a stalklike projection, variously known as the isthmus, beak, or appendage. It is not so deeply colored as the conidium and may even be hyaline or nearly so. It may be quite short and swollen or long and slender, nonseptate, uniseptate, or even multiseptate (fig. 1). It is formed by a growth or a budding of the conidium at a time when it is the youngest of the chain, that is, when it occupies the distal position in the chain. From this outgrowth the next spore in the chain is developed. In descriptions of species of Alternaria the term conidiophore is usually applied only to the outgrowth from the conidia-bearing hypha which supports the first formed conidium of the chain. In this sense it is considered as the conidiophore for the whole chain. The so-called isthmus or beak may also be considered as a conidiophore, not in relation to the conidium from which it is an outgrowth and to which it remains attached, but in relation to the distally situated conidium which grew out from it. This view is supported by the fact that it becomes separated from this conidium as most conidiophores become separated from the conidia which they bear. In one form studied the so-called isthmi or beaks tended finally to collapse and disintegrate, which is also a fairly common behavior of conidiophores. A consideration of isthmi as conidiophores also offers an explanation as to why the end spores of the chains often have no isthmi or have especially long ones. In the former case budding has not started; in the latter the long, septate hyphalike structures which may become new conidia and conidiophores have been formed. The same sort of budding, but at right angles, makes the branches of the chain. The isthmi or conidiophores often do not have as thick walls as the conidia. The tip often appears to be swollen and turgid, a condition which facilitates the breaking up of the chain through lessening the line of contact between the isthmus and the immediately distal conidium. When, however, a breaking up of the chain does not occur at this stage, as often happens when the chain lies along the surface of the culture medium, it is finally brought about by the shrinkage and disintegration of the isthmi. In this way, also, they perform a separative function. They are often more than one-celled and are incapable of germination. In the case of mature conidia the dividing line between conidium and isthmus (conidiophore) is easily determined by the position of the convex end of the conidium and by the greater width and deeper color of the conidium; in older conidia the disintegration of the isthmus may also indicate the dividing line.

TECHNICAL DESCRIPTION

Alternaria mali.—Realizing that the original description of *Alternaria mali* (*16*, *p. 58*) was too brief to be of proper use in identification, the writer undertook a more careful study of the fungus as it develops naturally on apple leaves, as it appears on apple leaves left in moist chambers for several days, and as it grows on artificial culture media. It is hoped

that the description which follows is sufficiently detailed to permit of identification by subsequent investigators, though lack of knowledge concerning the genus as a whole prevents one from knowing what characters should receive particular attention.

Hyphae on the surface of apple leaves are normally scant or lacking, dark olive when present; but in moist chambers they are abundant and

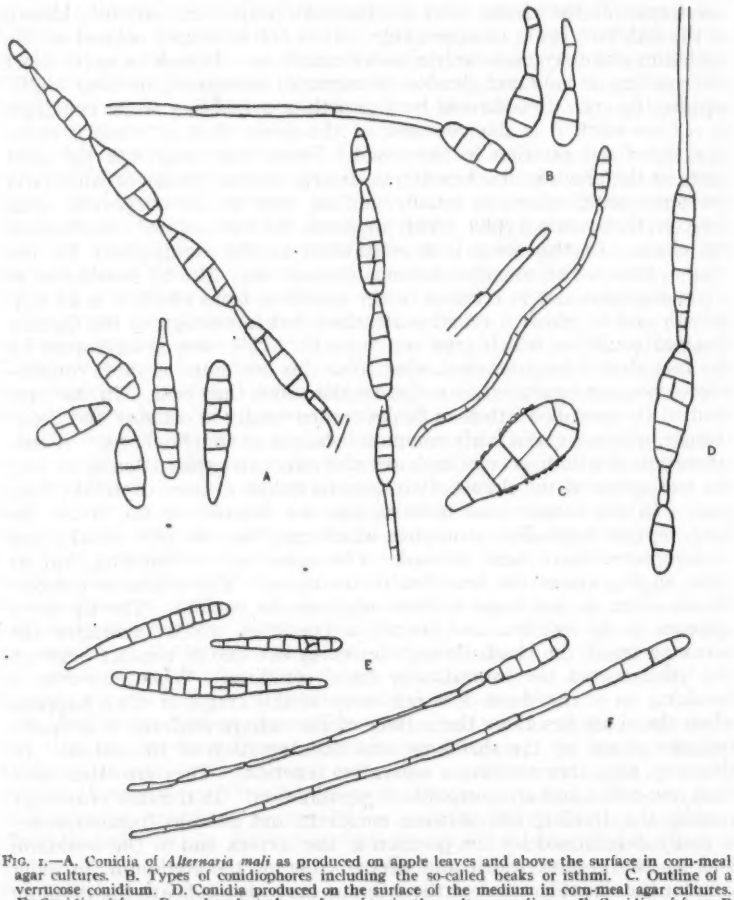


FIG. 1.—A. Conidia of *Alternaria mali* as produced on apple leaves and above the surface in corn-meal agar cultures. B. Types of conidiophores including the so-called beaks or isthmi. C. Outline of a verrucose conidium. D. Conidia produced on the surface of the medium in corn-meal agar cultures. E. Conidia of form B produced at the surface of or in the culture medium. F. Conidia of form B with long so-called beaks or isthmi. A, B, D, E, and F × 325. C × 525.

are light gray in mass with occasional darker areas. In corn-meal agar cultures the hyphae at or near the surface of the medium vary from nearly hyaline to dark olive, the latter predominating. On apple leaves their arrangement is usually fasciculate, but on artificial media they may lie parallel to one another and nearly in one plane, forming a sheet or layer. The hyphal segments are short, often no longer than their width, without constrictions at the septa. They are 3 to 8 μ wide and seldom

more than twice as long, mostly unbranched except that conidiophores may spring from them. Aerial hyphae either on apple leaves kept in moist chambers or in corn-meal agar cultures are nearly hyaline to light amber, often geniculate, branched, occasionally joined together (reticulate), segments relatively much longer than in surface hyphae 3 to 5 μ wide, length quite variable 5 to 25 μ or longer, often constricted at the septa, especially when old.

In old cultures the hyphal segments often become swollen to form chains of chlamydosporelike bodies.

The conidia (fig. 1 and Pl. 1, C) on apple leaves form tiny black masses, which separate easily from the leaf. In corn-meal agar cultures, chains of conidia form a dark carpet-like mass over the surface of the medium. Conidia also occur to some extent scattered through the aerial hyphae and at the surface of or in the medium. They are light amber to very dark olive or nearly black, those produced just above the surface of the medium being the darkest and those produced on aerial hyphae well above the medium being the lightest. The typical arrangement is in simple or branched chains. Septation may be transverse and longitudinal (muriform), with constriction at the septa especially when old. Verrucose outer walls (fig. 1, C) are common and sometimes the rule. The number of septa vary with the size and shape of the conidium. In general, conidia produced along the surface of or in the artificial culture medium are much longer and narrower than those produced in chains projecting above the medium or on aerial hyphae (fig. 1, D, E). Narrow conidia are more often without longitudinal septa.

The conidiophore subtending the first-formed conidium of a chain is produced at approximately right angles to the hypha (fig. 1, A). It is often short and nonseptate or one-septate, but it may be long and multiseptate (fig. 1, B). Usually, it is broader than the hypha from which it was produced. When the conidium separates from it, a dark-colored scar is seen at the point of attachment (fig. 1, B). It is usually smooth with a swollen apex, but in older cultures it may be at least as many as three times geniculate, each joint denoting the origin of a chain of spores (fig. 1, B). These conidiophores of the initial spores of the chains are usually fasciculate on apple leaves in nature, and are often so in artificial cultures.

The conidiophores (isthmi) supporting subsequent members of the chain are outgrowths from terminal (distal) segments of conidia, or in branched chains, lateral outgrowths from nonterminal segments. They resemble the conidiophore of the initial conidium very closely. They are swollen at the tip, may be nonseptate or multiseptate, short or long, straight, angled, or geniculate (fig. 1, B). In color they range from nearly hyaline to olive, the former predominating except when old.

In all the following measurements and in all consideration of septation the conidiophore or isthmus is not regarded as part of the conidium. Unless otherwise specified the word "septate" means "transversely septate." In each series, the measurements (in microns) are of 50 conidia taken at random. Conidiophores were measured at their greatest width.

Measurements of conidia from spots on apple leaves. (Arlington Experiment Farm, Rosslyn, Va., September, 1921):

	Average.
1-septate (2 per cent), 16 x 9	16 x 9
2-septate (10 per cent), 19 to 22 x 8 to 13	21 x 11
3-septate (56 per cent), 20 to 29 x 8 to 13	25 x 12
4-septate (22 per cent), 27 to 38 x 9 to 15	32 x 13
5-septate (10 per cent), 42 to 46 x 9 to 15	43 x 13
With longitudinal septation (78 per cent) width 11 to 14	13
Without longitudinal septation (22 per cent) width 8 to 13	10
Conidiophores (isthmi), 2 to 30 x 3 to 5	6 x 4
Number of septa for all the conidia	3.28
Dimensions of all the conidia	28 x 12

Measurements of conidia from a nine-day-old culture on a corn-meal agar plate (fungus newly isolated from spots on apple leaves):

	Average.
1-septate (2 per cent), 13 x 7	13 x 7
2-septate (18 per cent), 17 to 21 x 8 to 13	19 x 11
3-septate (46 per cent), 21 to 29 x 9 to 13	24 x 11
4-septate (22 per cent), 29 to 37 x 9 to 14	34 x 12
5-septate (6 per cent), 34 to 38 x 8 to 13	36 x 11
6-septate (6 per cent), 36 to 46 x 10 to 13	41 x 12
With longitudinal septation (76 per cent), width 10 to 14	12
Without longitudinal septation (24 per cent), width 7 to 11	9
Conidiphores (isthmi) 2 to 12 x 2 to 5	5 x 4
Number of septa of all the conidia	3.30
Dimensions of all the conidia	27 x 11

Measurements of conidia from a nine-day-old culture on a corn-meal agar plate (fungus isolated from apple leaves and grown in artificial culture about one year):

	Average.
1-septate (8 per cent), 13 to 15 x 8 to 9	14 x 8
2-septate (20 per cent), 17 to 25 x 8 to 13	20 x 10
3-septate (56 per cent), 20 to 29 x 8 to 13	25 x 11
4-septate (8 per cent), 25 to 34 x 9 to 12	30 x 11
5-septate (4 per cent), 34 x 11 to 12	34 x 12
6-septate (4 per cent), 42 x 9 to 13	42 x 11
With longitudinal septation, 58 per cent, width 9 to 13	12
Without longitudinal septation, 42 per cent, width 8 to 11	9
Conidiophores (isthmi), 3 to 12 x 3 to 5	5 x 4
Number of septa for all the conidia	2.92
Dimensions of all the conidia	24 x 11

Alternaria mali, in addition to causing enlargements of dead spots on apple leaves, is capable of infecting the fruit. It is reported by Reed and Crabill (*15*) as causing a soft rot of the fruit of the York Imperial variety of apple following "skin crack" and "York spot."

Wolf (*21*), Longyear (*13*), Clinton (*5*), Stakman and Rose (*19*), and Cook and Martin (*6*) reported on species of Alternaria isolated from apple fruits, but gave no descriptions of them. Longyear's drawings show that his fungus greatly resembles and is possibly identical with *Alternaria mali*. Longyear also found the fungus growing on the leaves and sprouts of the pear.

McInnes (*14*) and Horne (*10*) give descriptions of the species of Alternaria which they found in dead spots on apple fruits. Of these species, *Alternaria pomicola* Horne has much larger spores than *Alternaria mali*. The *Alternaria tenuis* variety X of McInnes resembles *Alternaria mali* much more closely but has somewhat larger conidia.

From zonate spots on leaves of the common lilac growing near the apple trees at Arlington Experiment Farm, from which *Alternaria mali* was obtained, an Alternaria was isolated whose conidial measurements closely approximate those of *Alternaria mali*. In corn-meal agar cultures, however, it forms a thick olive green mat over the medium which is quite different from any observed growth of *Alternaria mali*.

VARIATIONS IN ALTERNARIA MALI

Variations, mutations, and races or strains among species of the "Fungi Imperfecti" have been noted by Bonar (*2*), Brierley (*3*), Burger (*4*), Crabill (*8*), La Rue (*12*), Shear and Wood (*18*), Stevens (*20*), and others. The observation that many of the conidia of *Alternaria mali* have verrucose walls induced the writer to attempt to secure by selection a race having smooth conidia exclusively and another having verrucose conidia only. Starting with the progeny of a single conidium, selections of nonverrucose conidia were made through one series, while in another series attempts were made to select those having the highest degree of verrucosity. The method of isolating the selected spores has been described by the writer (*17*) in a previous publication. It was thought that continued selection might bring success, but after 22 generations, covering a period of two years, no difference in verrucosity could be noted between the conidia of the two series. The results of these selections agree with those obtained by La Rue (*12*) in his selections for spore length and length of spore appendages in *Pestalozzia guepini*. It is possible that environment is the sole reason for the variation in verrucosity, but the difficulties surrounding such attempts at selection are very great and no conclusion should be drawn. One can not be sure that out of all the conidia produced in the selected culture he is choosing those showing the greatest verrucosity. Neither can he be certain that the conidium which he considers as smooth might not become verrucose when older. Thus he may be simply selecting along an average. It must also be remembered that a single conidium of Alternaria is really not a single but a composite conidium usually consisting of many parts each capable of independent germination. The chance for variation in the progeny of a single conidium accordingly may be very great.

While carrying on this work the writer observed a plate culture in which one section of the growth appeared quite different from the remainder. In this part, which will be designated as "A," practically no aerial mycelium was produced, but there was a dark carpetlike mass over the surface of the medium, with olivaceous conidia produced in large numbers. The remainder of the growth, which will be designated as "B," had abundant gray aerial mycelium with a scant production of long amber-colored conidia occurring in long chains running along the surface of the medium and parallel to it (fig. 1, E, F). Selections were made from each of these two forms for the purpose of attempting to establish "pure lines." Transfers were made weekly from the growths of previous transfers showing the greatest growth of A and B, respectively. The selections were grown side by side, one of A and one of B on corn-meal agar in the same Petri dish. From the first, selection A showed but little tendency to break up into A and B. After the tenth selection it came true until the cultures were discarded. B broke up into A and B sections with great constancy during the first 57 selections, though the

B parts of the growth were usually much the larger. From the fifty-eighth to the sixty-ninth and last selection B remained constant. (Pl. 1, A, Pl. 2, A, B.)

We thus have two races arising from a single conidium, neither of which in culture is exactly like the parent. A lacks the aerial hyphae of the parent, while B fails to produce the thin carpetlike layer bearing characteristic conidia, producing, instead, the long slender spores at or beneath the surface of the culture medium. B grows more rapidly than A. There was no chance that A and B were from a mixed or contaminated culture, for they were not only the progeny of a single conidium, but of a succession of 15 singly selected conidia.

Brierley (*3*) suggests that while variations in the "Fungi Imperfecti" may be due to mutation, they may perhaps be more wisely interpreted in terms of the splitting of an originally impure genetic constitution or of gametic or somatic segregation from heterozygotes. In fungi not known to have a sexual stage, he suggests the possibility of genetic contamination by the fusion of hyphal cells. Until such contaminations can be shown to occur, it seems more logical to consider the aberrant strains as due to mutation while admitting the possibility of genetical contamination. The fact that neither of the two races of Alternaria was exactly like the parent lends some support to the genetical contamination theory.

The following measurements were obtained from 50 conidia of each race taken at random from nine-day-old cultures growing side by side in a corn-meal agar plate. Conidial measurements are in microns and do not include conidiophores (isthmi). Unless otherwise specified the word "septate" means "transversely septate."

RACE A

	Average.
1-septate (4 per cent), 9 to 13 x 7 to 8	11 x 8
2-septate (26 per cent), 15 to 21 x 7 to 11	18 x 8
3-septate (34 per cent), 21 to 28 x 7 to 11	23 x 9
4-septate (10 per cent), 27 to 36 x 8 to 12	32 x 10
5-septate (18 per cent), 34 to 38 x 8 to 12	35 x 9
6-septate (6 per cent), 38 to 42 x 9 to 12	39 x 10
7-septate (2 per cent), 42 x 11	42 x 11
With longitudinal septation (36 per cent), width 8 to 12	10
Without longitudinal septation (64 per cent), width 7 to 11	8
Conidiophores (isthmi) 4 to 6 x 3 to 6	5 x 4
Number of septa of all the conidia	3.38
Dimensions of all the conidia	26 x 9

RACE B

	Average.
3-septate (12 per cent), 27 to 34 x 8 to 12	32 x 10
4-septate (18 per cent), 34 to 42 x 8 to 9	39 x 9
5-septate (22 per cent), 38 to 57 x 7 to 9	45 x 8
6-septate (18 per cent), 40 to 55 x 8 to 12	48 x 9
7-septate (20 per cent), 57 to 67 x 7 to 13	60 x 10
8-septate (4 per cent), 76 x 9 to 10	76 x 10
9-septate (4 per cent), 63 to 80 x 11	72 x 11
10-septate (2 per cent), 88 x 10	88 x 10
With longitudinal septation (18 per cent), width 10 to 13	12
Without longitudinal septation (82 per cent), width 7 to 10	9
Conidiophores (isthmi) 5 to 14 x 4 to 6	8 x 5
Number of septa for all the conidia	5.54
Dimensions of all the conidia	49 x 9

The following measurements of 50 conidia from a 16-day-old culture of race B on corn-meal agar are of interest because of the long conidiophores (isthmi):

	Average.
2-septate (2 per cent), 21 x 8	21 x 8
3-septate (10 per cent), 22 to 39 x 7 to 9	30 x 9
4-septate (18 per cent), 32 to 42 x 8 to 9	37 x 8
5-septate (30 per cent), 32 to 52 x 8 to 11	40 x 9
6-septate (22 per cent), 44 to 52 x 8 to 10	48 x 9
7-septate (14 per cent), 48 to 59 x 8 to 12	54 x 9
9-septate (4 per cent), 52 to 63 x 8	58 x 8
With longitudinal septation (16 per cent), width 9 to 12	10
Without longitudinal septation (84 per cent), width 7 to 9	8
Conidiophores (isthmi) 6 to 59 x 3 to 5	18 x 4
Conidiophores having a length of more than 20 were 1 to 4 septate.	
Number of septa of all the conidia	5.22
Dimensions of all the conidia	43 x 8

The larger conidia and conidiophores of race B were possibly due to the nutritional advantages incident upon their location in or at the surface of the culture medium. It should be noted that the measurements of race A and the parent are not greatly different. The differences between A and B were not due to differences of environment, since they were grown side by side in the same plate, but it is possible that the conditions attending growth on culture media may have acted as a stimulus to the disclosure of certain differences not apparent in nature.

Mutations were also observed in other single conidium cultures of *Alternaria mali* from apple leaves and single conidium cultures of the Alternaria isolated from lilac leaves. On the other hand, species from cranberry and blueberry supplied by Dr. Neil E. Stevens and subsequently grown by the writer from single conidia showed no tendency toward mutation. An Alternaria from blackberry supplied by Dr. B. O. Dodge showed two distinct forms from the first culture. Single conidium cultures were not used here, however, and it is possible that two distinct species were present. A culture of *Alternaria tenuis* supplied by Dr. Johanna Westerdÿk showed no tendency toward variation, though grown in plate cultures with frequent transfers.

SUMMARY

Alternaria mali often enters apple leaves through injured or dead spots and forms about them characteristically crescent-shaped or circular enlargements. A brief discussion of some of the morphological characters of the genus Alternaria based on observation of species from apple, lilac, cranberry, blueberry, blackberry, and forsythia is given. *A. mali* is described more fully than formerly and more detailed measurements of conidiophores and variously septate conidia are given. Variants, considered as due to mutation, were found in "single spore" cultures of *A. mali*.

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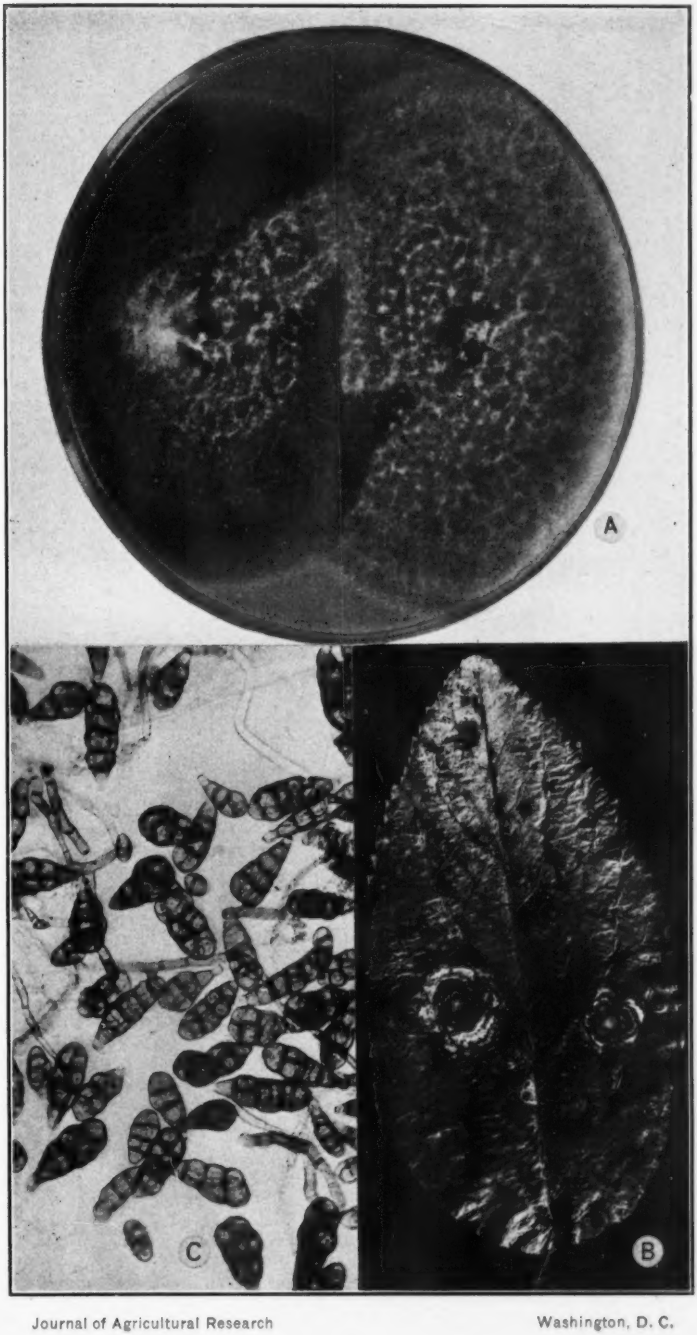
PLATE 1

A.—*Alternaria mali*. Cultures of forms A and B in a Petri dish of corn-meal agar. Each has broken up into the two forms.

B.—Spots on an apple leaf showing about the original central spot the type of enlargements caused by *Alternaria mali*.

C.—Conidia of *Alternaria mali* from a culture on corn-meal agar. ×440.


A
B
C

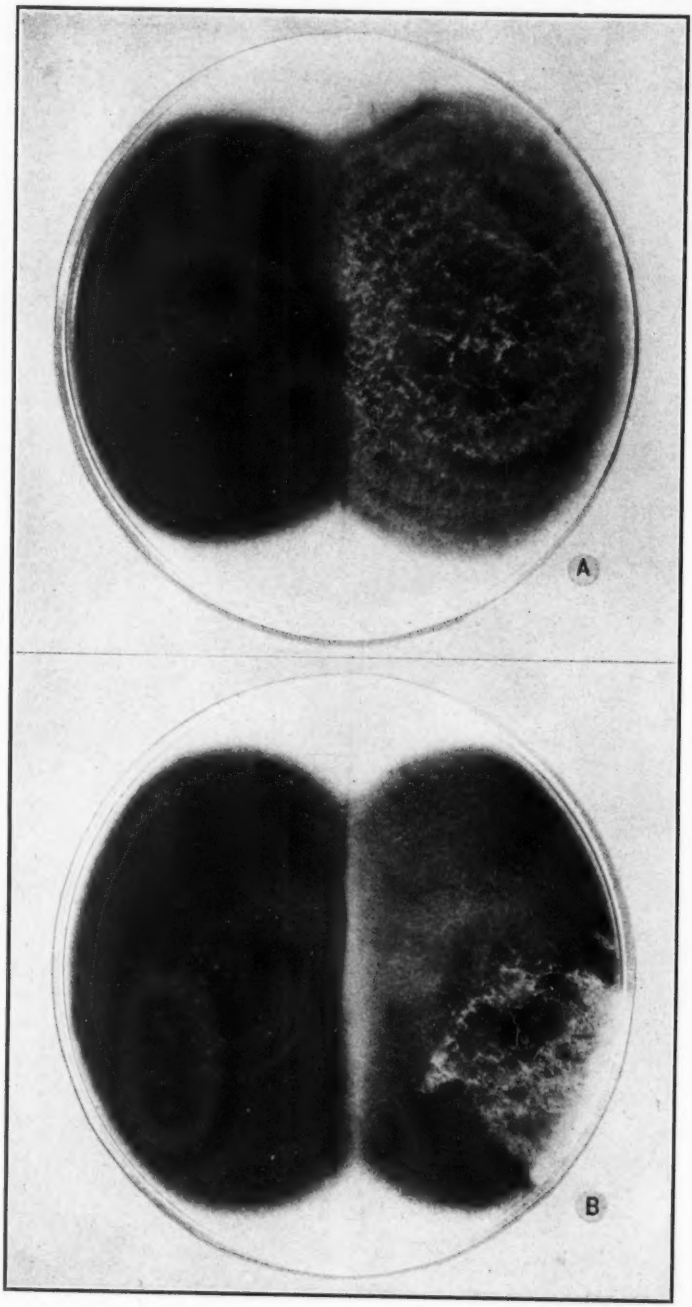

A
B

PLATE 2

Alternaria mali. Cultures of forms A and B in Petri dishes of corn-meal agar.
A.—Both forms have come true.
B.—Form A has come true but B has broken up, producing much more of A than of B.

NATURAL ANTISHEEP AMBOCEPTOR AND COMPLEMENT IN THE BLOOD OF FOWLS [1]

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INTRODUCTION

The attention of the writers was first directed to the dissolving action of fresh chicken serum upon the blood corpuscles of the sheep during some hemolytic experiments with the blood serum of chickens known to be carriers of *Bacterium pullorum*. Whether the lytic action of the chicken serum was due to the presence of a natural antisheep amboceptor or to complement, could not be stated. An endeavor was therefore made to determine the presence of these elements in the serum.

REVIEW OF LITERATURE

Bordet (*2*) [2] was the first to call attention to the hemolytic and hemagglutinating action of chicken serum upon the cells of other animals. He also noted the marked susceptibility of rabbit corpuscles to the action of this serum. He was able to produce an antihemolysin that prevented the action of chicken serum upon rabbit corpuscles. In discussing the presence of sensibilisatrice in normal sera he states that it is necessary to be cautious in drawing conclusions. Because a serum agglutinates blood cells does not necessarily mean that they are sensitized to the action of alexin. For example, he states that rabbit corpuscles, although strongly agglutinated by chicken serum heated to 55° C., are then no more susceptible to the lytic action of normal guinea-pig serum than are rabbit corpuscles untreated by heated chicken serum.

Müller (*5*) verified Bordet's observation, but concluded that the hemolytic action of chicken serum is to be ascribed to an amboceptor-alexin combination. This author did not succeed in separating amboceptor and alexin by use of absorption in the cold as recommended by Ehrlich. Müller sought to demonstrate the presence of the two components by adding an amount of fresh chicken serum that would not hemolyze a given amount of rabbit cells and by the addition of inactivated (heated) serum so to reinforce the hemolytic strength that solution of the blood corpuscles would take place. His results were negative. The negative results were thought to be due to the fact that chicken serum has so little alexin that it could not activate the amboceptor present and would naturally exert no effect. To prove this point he increased the alexin of the chicken serum by injecting the birds with various substances such as peptone, bouillon and aleuronat. By this method the alexin content was increased so that from 0.03 to 0.07 cc. of this fresh serum would cause complete hemolysis of rabbit corpuscles in the presence of 0.2 to 0.3 cc. of heated chicken serum. The fresh serum alone was less active than the fresh serum plus heated serum. The heated

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[2] Reference is made by number (italic) to "Literature cited," p. 715.

serum alone was completely inactive. It was found that about 0.15 cc. of fresh pigeon serum hemolyzed 1 cc. of a 5 per cent suspension of rabbit corpuscles in the presence of 0.2 cc. of inactivated chicken serum.

Lüdke (*4*) discusses hemagglutinins in chicken and duck serum for the red blood corpuscles of other species. He found that fresh serum from a 3 day-old chick agglutinated and dissolved human and rabbit blood corpuscles in about 10 minutes, but this serum lost the lytic power and most of the agglutinating power after being heated for one-half hour at 55° C.

Serum from a normal 3-day-old duck agglutinated blood corpuscles of the sheep almost immediately, in dilutions of 1 part to 10, and slightly in dilutions of 1 part to 20. The hemagglutinins disappeared when the serum was heated to 60° to 65° C. Fresh duck serum caused complete agglutination of guinea-pig corpuscles in 5 minutes. Such serum showed a trace of agglutination for human corpuscles and a strong agglutination of rabbit corpuscles followed by lysis. After heating this serum at 50° to 55° C. there was partial agglutination of guinea-pig cells, none for human corpuscles and complete agglutination in 5 minutes for those of the rabbit. After heating at 55° to 60° C. no agglutination for guinea pig or human corpuscles was observed, but complete agglutination for rabbit corpuscles occurred in one-half hour.

Rywosch (*7*) studied the hemolytic action of the blood of embryo chicks upon rabbit corpuscles. No hemolysis could be demonstrated with embryo chick serum. One-tenth cc. of serum from a chick 5 days of age caused complete hemolysis of 0.2 cc. of 5 per cent rabbit cell suspension and was almost complete for 0.5 cc. This author found that 0.08 cc. of serum from an adult bird caused complete hemolysis of 1 cc. of 5 per cent suspension of rabbit corpuscles. An attempt to show that the negative results were due to lack of amboceptor failed. These tests were conducted with varying amounts of chick embryo serum and inactivated serum from adult birds. Serum from 5-day-old chicks added to the inactivated serum from adult birds caused complete hemolysis. This author seemed to think that the embryo serum lacked both amboceptor and complement for rabbit cells.

Sherman (*8*) examined blood from chick embryos and reported as follows: In no case was lysin found in any embryo except those of 21 days' incubation, and in this case the chicks were pecking their way out of the shell. Their serum contained lysin for rabbit erythrocytes only, 0.1 cc. of serum being required to lake completely 0.1 cc. of a 1 per cent erythrocyte suspension. Complement was found in the embryo serums of 17 and 21 days' incubation; it required 0.05 cc. of the serum of the younger embryo and 0.1 cc. of that of the older to lake completely 0.1 cc. of 1 per cent suspension of rabbit erythrocytes when 1 unit of amboceptor (dog) was added. No embryo serum examined contained complement for sheep, goat, or human erythrocytes.

Rissling (*6*) studied the hemolytic and hemagglutinating action of the serum of various species upon the blood corpuscles of others. He used fresh blood corpuscles. These were washed twice and used in 1 per cent suspension in salt solution. For agglutination tests the serum was inactivated at 56° C. for one-half hour. The tests were incubated at 37° C. for two hours. Goose serum was found to agglutinate sheep cells when diluted to 1 part to 10. Duck and chicken serum in these dilutions did not agglutinate sheep cells. Chicken serum caused agglutination of corpuscles of various animals in the following dilutions: Human, 1 to 50;

horse, 1 to 50; swine, 1 to 300; rabbit, 1 to 300; guinea pig, 1 to 20; goose, 1 to 80; duck, 1 to 90; and pigeon, 1 to 90.

In his hemolytic experiments Rissling used a 5 per cent suspension of corpuscles. The serum was obtained fresh. Goose, duck, pigeon, and chicken serum caused no hemolysis of sheep cells in amounts of 0.5 cc. Chicken serum was found to cause hemolysis of corpuscles of various animals when used in the following amounts: Human, 0.3 cc.; swine, trace in 0.1 cc., and complete in 0.4 cc. Chicken serum to the amount of 0.5 cc. did not hemolyze corpuscles of horse, ox, sheep, guinea pig, goose, duck, or pigeon.

Aschenheim (*1*) summarized the results of various authors concerning the lytic action of the serum of various animals upon the blood corpuscles of other animals. In the table incorporated in his article he attempted to show the occurrence of natural amboceptor but failed to demonstrate this for sheep corpuscles in fresh normal chicken serum.

Hyde (*3*), in studying the natural hemolytic antibody of chicken serum, found that 0.1 cc. of chicken serum consistently caused complete hemolysis of 0.1 cc. of a 1 to 4 suspension of corpuscles of rabbit, guinea pig, ox, sheep, and pigeon. The dissolving action, however, was most energetic for rabbit cells and least for those of the pigeon.

Hyde conducted some experiments on the reactivation of heated chicken serum. He was unable to do this by the usual procedure, but by a modification of the original technic, chicken serum inactivated by heat at 56° C. for 30 minutes, was reactivated for rabbit corpuscles with nonhemolytic doses of fresh chicken serum to practically its original hemolytic titer. The test was made by adding the different amounts of heated chicken serum to the tubes, salt solution was then added, followed by fresh chicken serum as a complement. The tubes were incubated for one hour, the corpuscles were then added and the incubation continued. It was found that chicken serum inactivated at temperatures between 53° and 58° C. could be reactivated almost to its original titer by this method. Somewhat similar results were obtained by use of guinea-pig serum as a complement.

EXPERIMENTAL DATA

A flock of 22 fowls was available for this study. All birds were bled from the heart. The samples of blood thus obtained were allowed to clot and the serum was removed to sterile tubes immediately after centrifugation.

SEPARATION OF AMBOCEPTOR AND COMPLEMENT

In order to make titrations of the ambocepter and complement separately, it was necessary to absorb the former with washed sheep cells at 0° C. The various samples of serum were placed in brine at a temperature of 0° C. A sheep-cell suspension was likewise placed in the bath. After sufficient time had elapsed to allow the temperature of the serum and cells to be lowered to 0° C., 3 cc. of the 5 per cent suspension of cells were added to 1 cc. of each sample of serum. The tubes were thoroughly shaken and immediately replaced in the bath where they were allowed to remain for one hour, which proved to be sufficient time for the absorption of hemolysin by the cells. Each sample was centrifuged and the supernatant fluid removed to sterile tubes. The sediment was resuspended in

a large quantity of cold saline and again thrown down in the centrifuge. After removing the supernatant fluid the sediment was resuspended in 4 cc. of saline.

TREATMENT OF SUPERNATANT FLUID

The supernatant fluid containing the complement represented a dilution of one in four. Gradually increasing quantities of this dilution were placed in a series of five tubes and to this was added one unit of antisheep hemolysin (rabbit) and 0.5 cc. of a 5 per cent suspension of sheep cells. Saline was added to make the total volume in each tube equal to 2 cc. A control tube was added which contained 0.5 cc. of diluted complement and sheep cells, to determine the presence of ambocepter. Table I gives the amount of each reagent used.

TABLE I.—*Titration of complement in chicken serum*

Tube No.	1	2	3	4	5	6
Supernatant fluid (complement)	0.2	0.4	0.6	0.8	1.0	0.5
Amboceptor (1 unit)	.1	.1	.1	.1	.1	.0
Cells (5 per cent)	.5	.5	.5	.5	.5	.5
Saline	1.2	1.0	.8	.6	.4	1.0

All tubes were incubated at 37° C. for one hour and placed in the ice box over night. The results are recorded in Table II.

TABLE II.—*The action of supernatant fluid (complement) and one unit of antisheep amboceptor (rabbit) on sheep cells*

	One unit of antisheep amboceptor (rabbit) and 0.5 cc. of 5 per cent sheep cells plus supernatant fluid.					0.5 per cent of sheep cells plus supernatant fluid.
Supernatant fluid..	0.2	0.4	0.6	0.8	1.0	0.5
Bird No.						
1	[a]o	o	o	o	[a]+	o
2	o	o	o	o	o	o
3	o	o	o	+	o	o
4	o	[a]++	++	++	++	o
5	o	+	+	+	++	o
6	o	o	o	o	o	o
7	o	o	o	o	o	o
8	o	+	++	++	[a]+++	o
9	o	o	o	+	+	o
10	o	o	+	+	o	o
11	o	o	o	+	o	o
12	+	+	++	+++	[a]++++	o
13	o	o	o	o	o	o
14	o	o	o	o	+	o
15	o	+	+	++	++	o
16	o	+	++	++	+++	o
17	o	o	o	o	+	o
18	o	o	o	o	o	o
19	o	o	o	o	o	o
20	o	o	o	o	o	o
21	o	o	o	o	o	o
22	o	o	o	o	o	o

[a] ++++=complete; +++=marked; ++=partial; +=trace; o=no hemolysis.

Examination of Table II shows that there is a complement in some chicken sera capable of activating an antisheep hemolysin (rabbit), when the ingredients are added in the usual order. However, there is considerable variation in the complement content of the various samples of sera tested.

TREATMENT OF SEDIMENT

One-half cubic centimeter of resuspended sediment was added to each of a series of 6 tubes. To the first 5 were added gradually increasing quantities of complement (guinea-pig serum diluted 1 to 10). Two-tenths cubic centimeters of this dilution of guinea-pig serum represented one unit of complement. The sixth tube served as a control to detect the presence of complement in the sediment suspension. Saline was added to each tube to make the total volume equal 2 cc. Table III gives the amounts of the various elements used.

All tubes were thoroughly shaken and placed in the incubator at 37° C. for one hour and then placed in the refrigerator over night. Table IV gives the results of each test.

TABLE III.—*Titration of amboceptor in chicken serum*

Tube No.	1	2	3	4	5	6
Suspended sediment	0.5	0.5	0.5	0.5	0.5	0.5
Complement (1–10)	.2	.4	.6	.8	1.0	.0
Saline	1.3	1.1	.9	.7	.5	1.5

TABLE IV.—*The hemolytic action of gradually increasing quantities of guinea-pig serum on resuspended sediment*

	0.5 cc. of resuspended sediment plus guinea-pig complement.					Control.
Complement (1–10)	0.2	0.4	0.6	0.8	1.0	0
Bird No.						
1	[a]0	0	0	0	[a]+	0
2	0	0	0	0	+	0
3	0	0	0	0	+	0
4	0	0	0	0	+	0
5	0	0	0	0	+	0
6	0	0	0	0	+	0
7	0	0	0	0	+	0
8	0	0	0	0	+	0
9	0	0	0	0	+	0
10	0	0	0	0	+	0
11	0	0	0	0	+	0
12	0	0	0	0	+	0
13	0	0	0	0	+	0
14	0	0	0	0	+	0
15	0	0	0	0	+	0
16	0	0	0	0	+	0
17	0	0	0	0	+	0
18	0	0	0	0	+	0
19	0	0	0	0	+	0
20	0	0	0	0	+	0
21	0	0	0	0	+	0
22	0	0	0	0	+	0

[a] +=trace; 0=no hemolysis.

An examination of Table IV shows that, under the conditions of the test, there is very little natural antisheep hemolysin in chicken serum that is capable of being activated by guinea-pig complement. No hemolysis occured in any tube containing less than 1 cc. of diluted complement, and the degree of hemolysis in these tubes appeared to be the same in all cases. A preliminary titration showed that 1 cc. of a 1 to 10 dilution of this pooled guinea-pig serum would not cause hemolysis of 0.5 cc. of a 5 per cent suspension of sheep cells.

Assuming the possibility that the natural antisheep hemolysin might be better activated by the native complement in chicken serum, it was decided to make such a test on each sample as indicated in Table IV.

The tubes were thoroughly shaken and placed in the incubator at 37° C. for one hour and placed in the refrigerator overnight. Table V gives the results obtained.

TABLE IV.—*The hemolytic action of fresh unheated chicken serum on sheep cells*

Tube.	1	2	3	4	5
Serum (undiluted)	0.1	0.2	0.3	0.4	0.5
Cells (5 per cent)	.5	.5	.5	.5	.5
Saline	1.4	1.3	1.2	1.1	1.0

TABLE V.—*The hemolytic and hemagglutinating action of fresh unheated chicken serum on sheep cells*

Bird No.	0.5 cc. of sheep cells plus serum.					Smallest quantity of serum which caused agglutination of blood cells.
	1–20	1–10	1–6.6	1–5	1–4	
	0.1 cc.	0.2 cc.	0.3 cc.	0.4 cc.	0.5 cc.	
						Cc.
1	[a]o	o	o	o	+	0.4
2	o	o	+	+	++	.1
3	o	o	+	+	Not run.	.2
4	o	+	[a]++	++	++	.2
5	o	o	o	++	++	.2
6	o	o	o	+	o	.3
7	o	o	o	o	o	.5
8	o	[a]+++	+++	+++	+++	.1
9	o	+	++	++	++	.2
10	o	+	++	++	++	.2
11	o	o	+	++	++	.2
12	o	+	+	++	++	.2
13	o	o	o	+	++	.2
14	o	o	o	+	++	.1
15	o	o	+	+	++	.3
16	o	o	++	++	++	.2
17	o	o	+	+	++	.2
18	o	o	+	++	++	.3
19	o	o	+	++	++	.2
20	o	o	o	o	+	[b].2
21	o	o	o	+	++	.2
22	o	[a]+	++	++	++	.2

[a] +++=marked; ++=partial; +=trace; o=no hemolysis. [b] Very slight.

In all sera tested some agglutination of the red cells took place. The smallest quantity of serum causing agglutination is indicated in Table V. It will be seen that some hemolysis occurred in every case except with the serum of fowl No. 7. Variation in the degree of hemolysis is evident; in general the complement titer corresponds in a measure to the hemolytic titer of the fresh serum. The hemagglutinin does not appear to correspond in strength to the complement titer. Nor do the hemagglutins correspond in strength to the hemolytic action of the fresh serum.

CONCLUSIONS

Most samples of fresh chicken serum are capable of causing some hemolysis of sheep cells. The small quantity of natural antisheep amboceptor contained in normal chicken serum may be separated from the complement by absorption with sheep cells at 0° C. The quantity of hemolysin does not vary appreciably in different individuals. The quantity of complement is small as compared with that contained in guinea-pig serum. A variation in the quantity of complement existed in the samples tested. Hemagglutinins for sheep cells are present in fowl sera but the quantity is not in proportion to the degree of hemolysis.

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